Status and Prospects for some MILC and Fermilab/MILC Projects

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Washington University
St. Louis
(MILC & Fermilab Lattice/MILC Collaborations)

New Horizons for Lattice Computations with Chiral Fermions
Brookhaven, May 14-16, 2012

Heavy-light Decay Constants

- ✦ Fermilab heavy quarks with MILC 2+1 Asqtad staggered light quarks
  - “Old data” project
    - 0.15 fm ≤ a ≤ 0.09 fm
    - 4 sources per configuration
    - renormalization mostly non-perturbative; 1-loop perturbation theory for remainder
    - to appear in PRD shortly
  - “New data” project: similar to above, but:
    - 0.15 fm ≤ a ≤ 0.045 fm
    - 2 to 5 times more configurations/ensemble
    - in progress
- ✦ For D system, ongoing HISQ project with MILC 2+1+1 HISQ quarks: more later.

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J. Simone, D. Toussaint, CB

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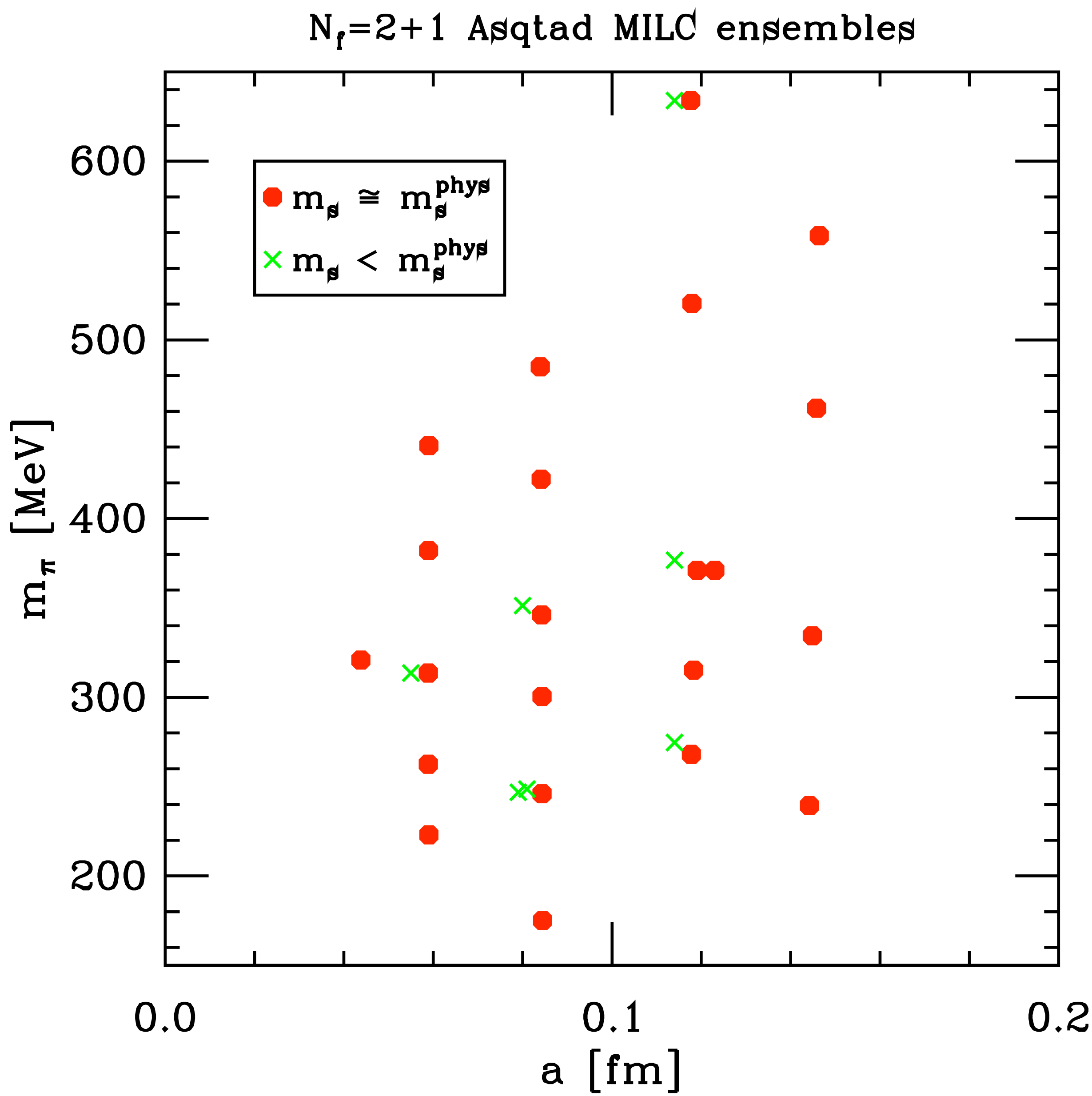

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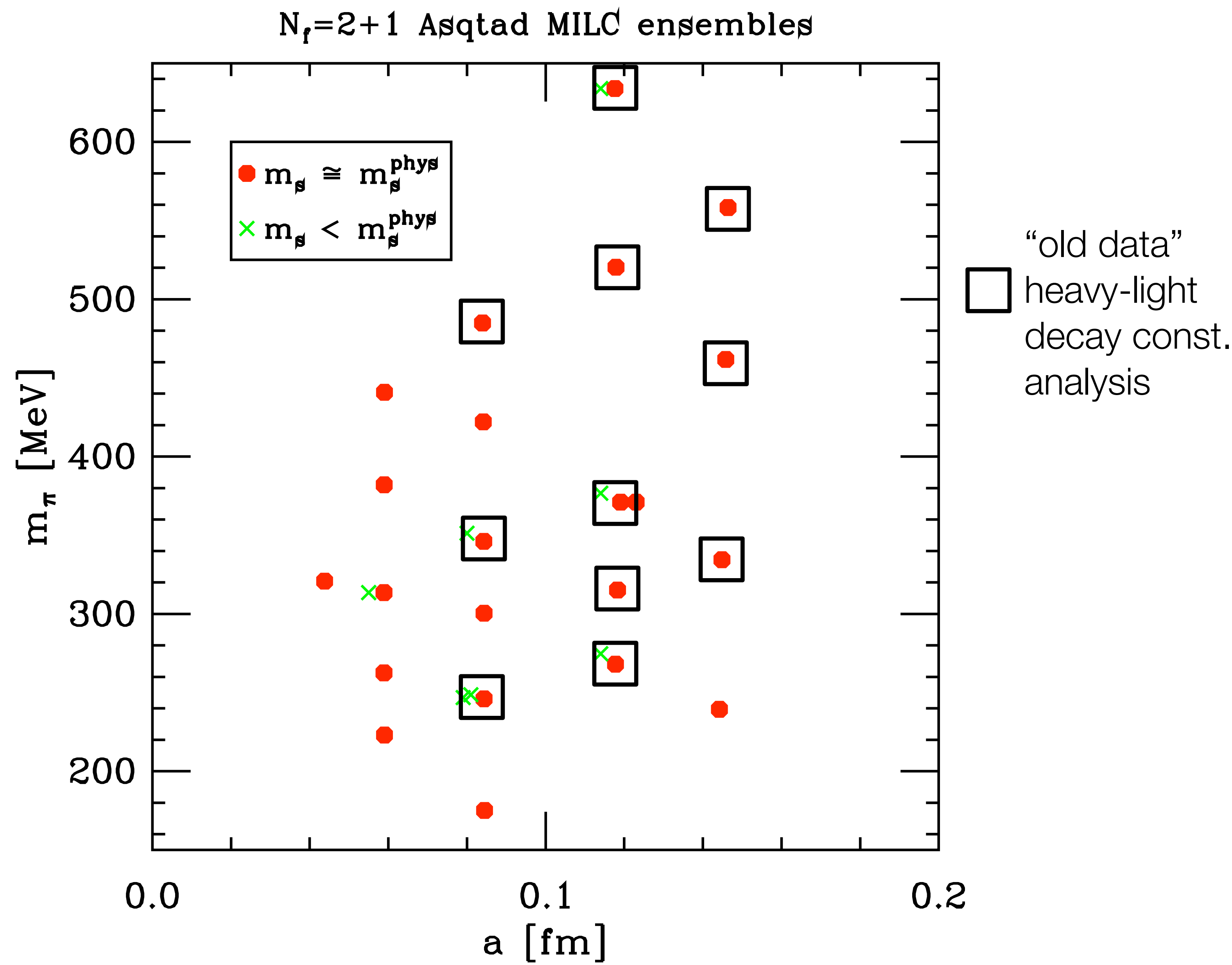

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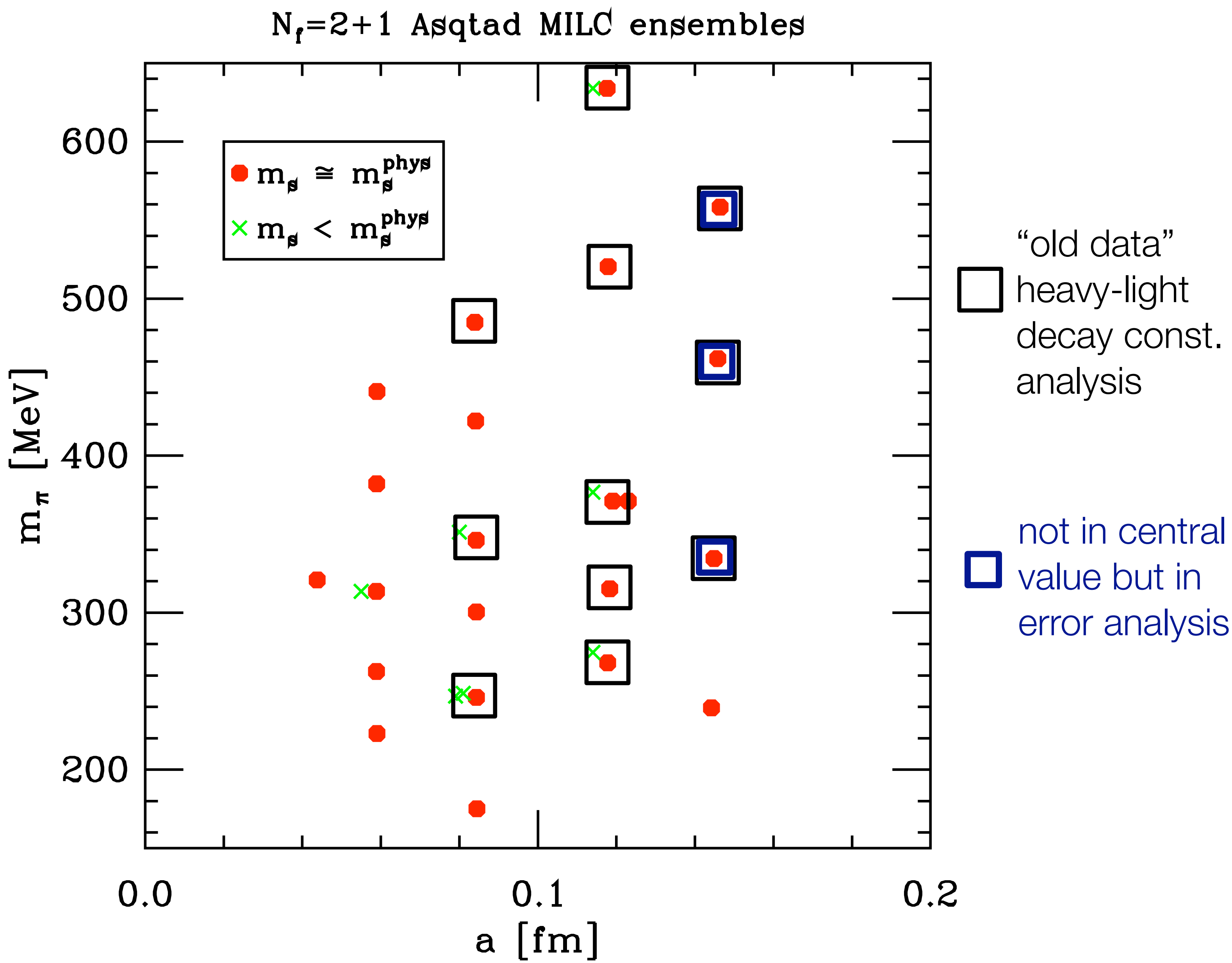
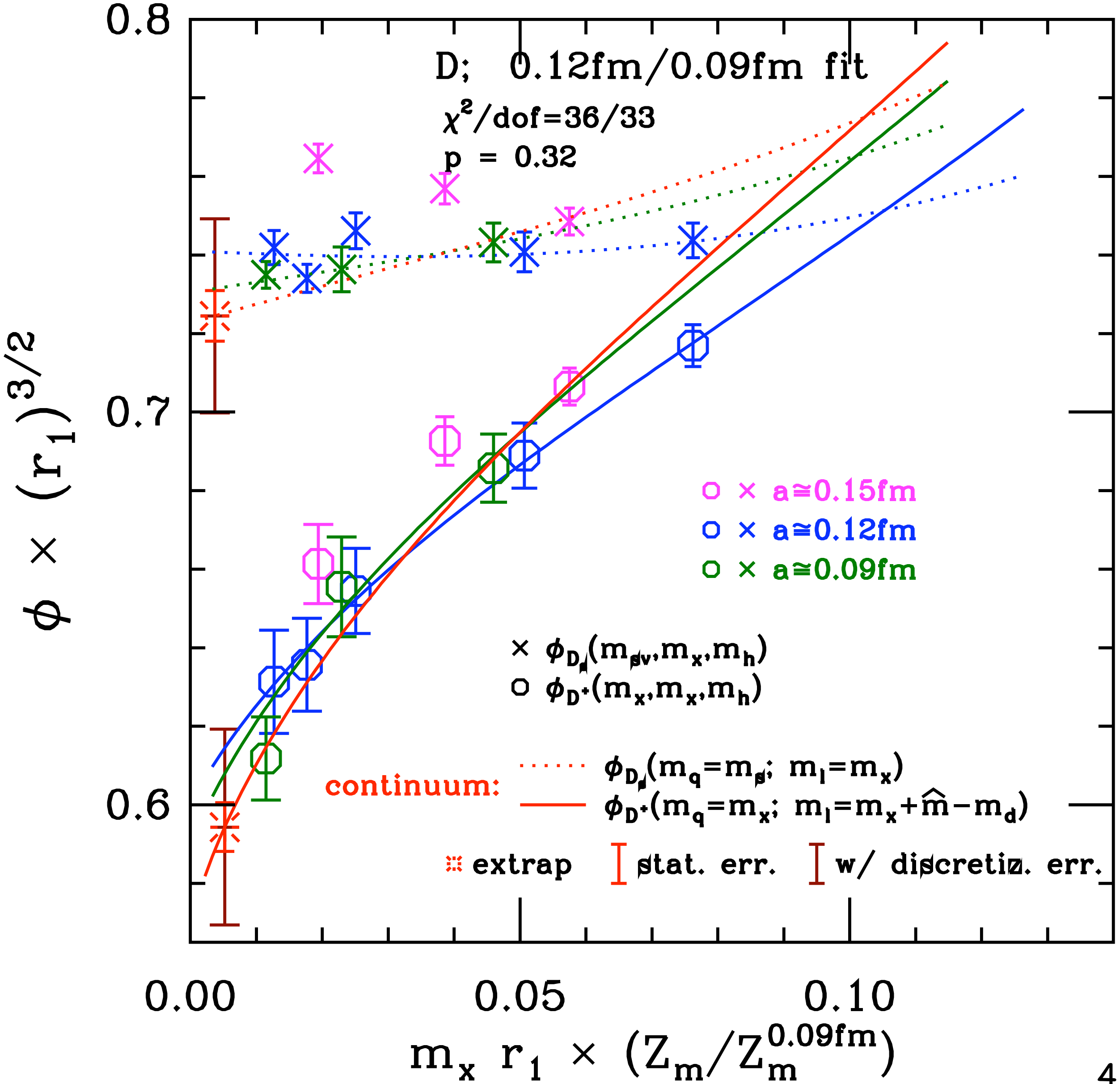


D system

- ✦ f_D as function of light valence mass m_q (= light sea mass m_l).
- ✦ f_{Ds} as function of light sea mass m_l.
  - valence mass held fixed ≈ m_s.
- ✦ a≅0.15 fm points not included in fit.
  - note qualitatively different behavior



B system

- ✦ f_B as function of light valence mass m_q (= light sea mass m_l).
- ✦ f_{Bs} as function of light sea mass m_l.
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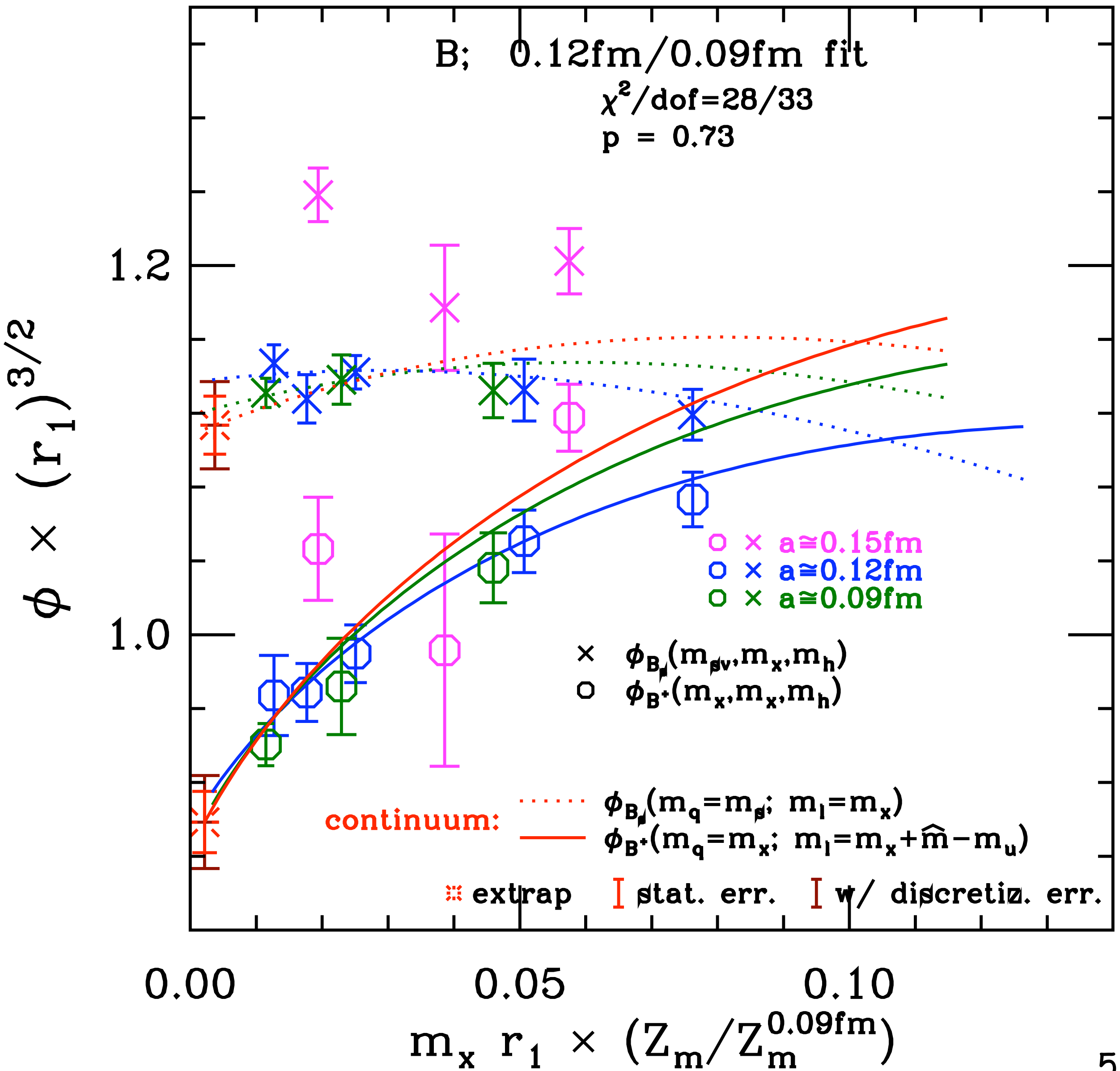
- ✦ a≅0.15 fm points not included in fit.
  - qual. different behavior + large stat. errors



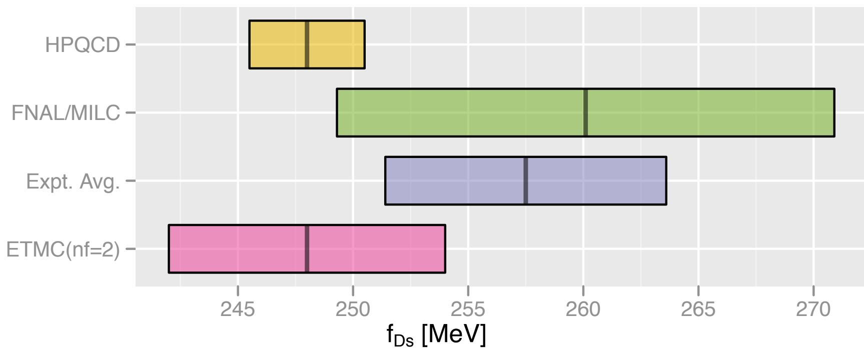
Fermilab/MILC Results

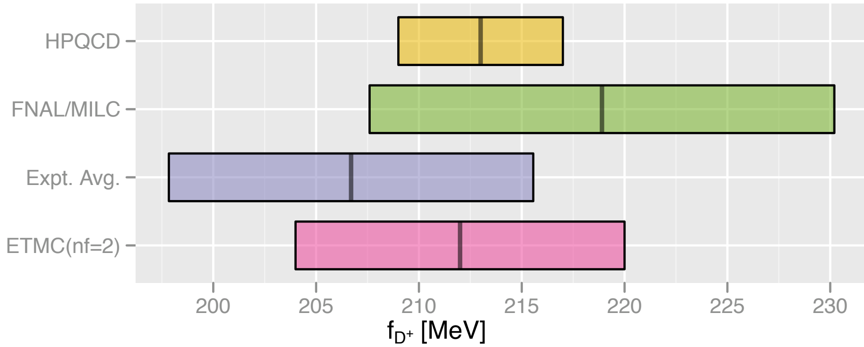
$$
\begin{aligned}
f_{D_s} &= 260.1 \pm 10.8 \text{ MeV} \\
f_{D^+} &= 218.9 \pm 11.3 \text{ MeV} \\
f_{D_s}/f_{D^+} &= 1.188 \pm 0.025 \\
f_{B_s} &= 242.0 \pm 9.5 \text{ MeV} \\
f_{B^+} &= 196.9 \pm 8.9 \text{ MeV} \\
f_{B_s}/f_{B^+} &= 1.229 \pm 0.026
\end{aligned}
$$

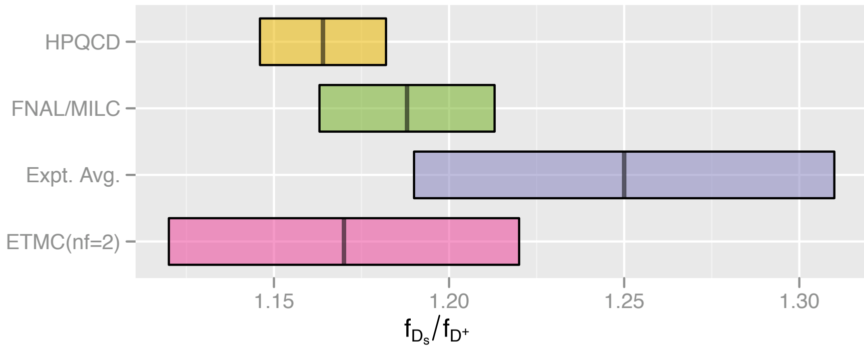
- errors include statistics and systematic errors
  - discretization errors for heavy & light quarks automatically included with statistics errors by our Bayesian procedure
  - have added on other systematics in quadrature

Comparison w/ other calculations & expt

D System







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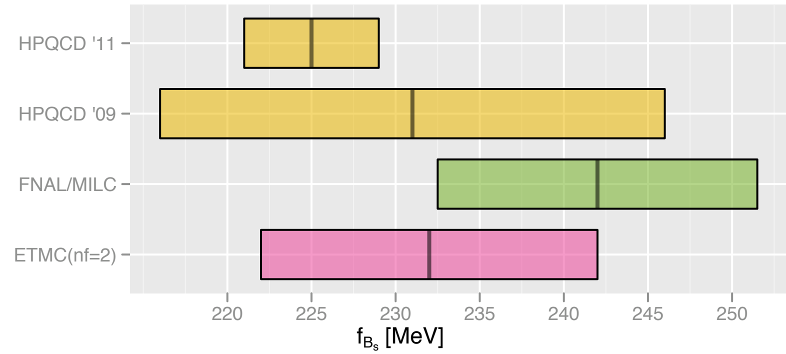

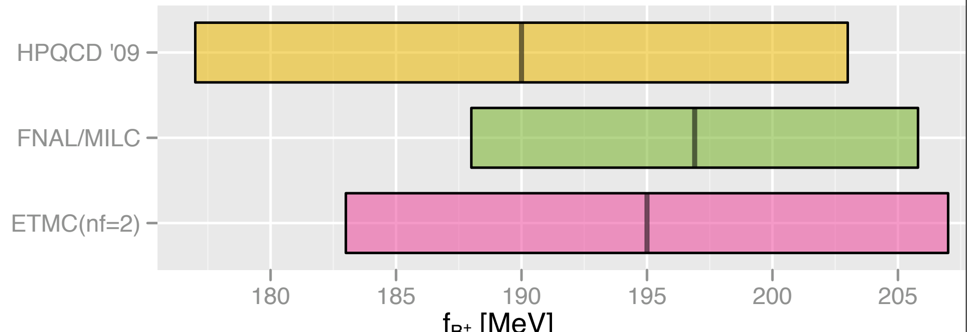

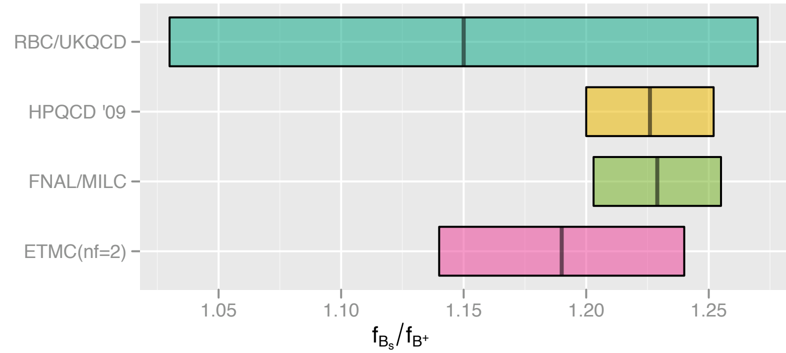

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E. Neil

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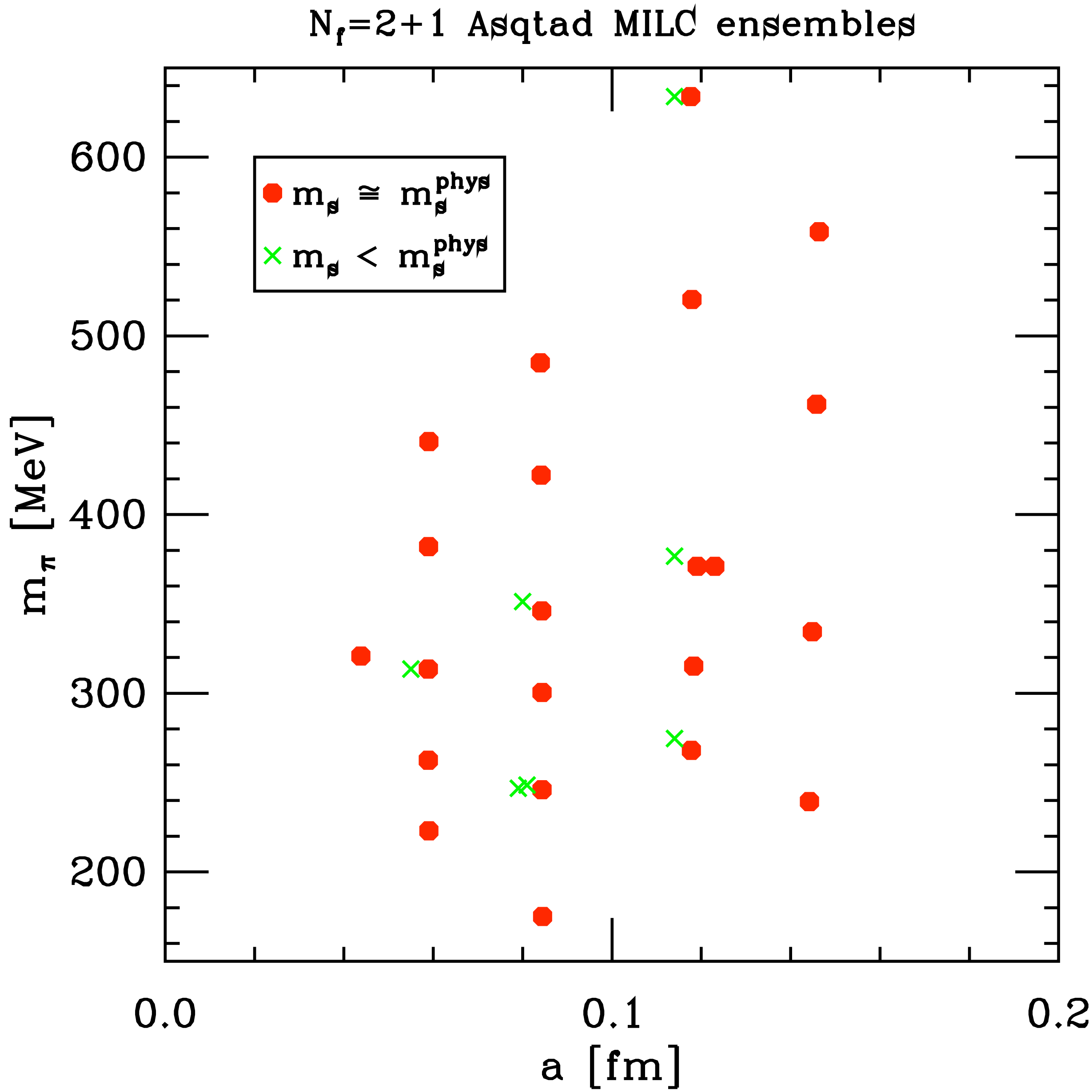

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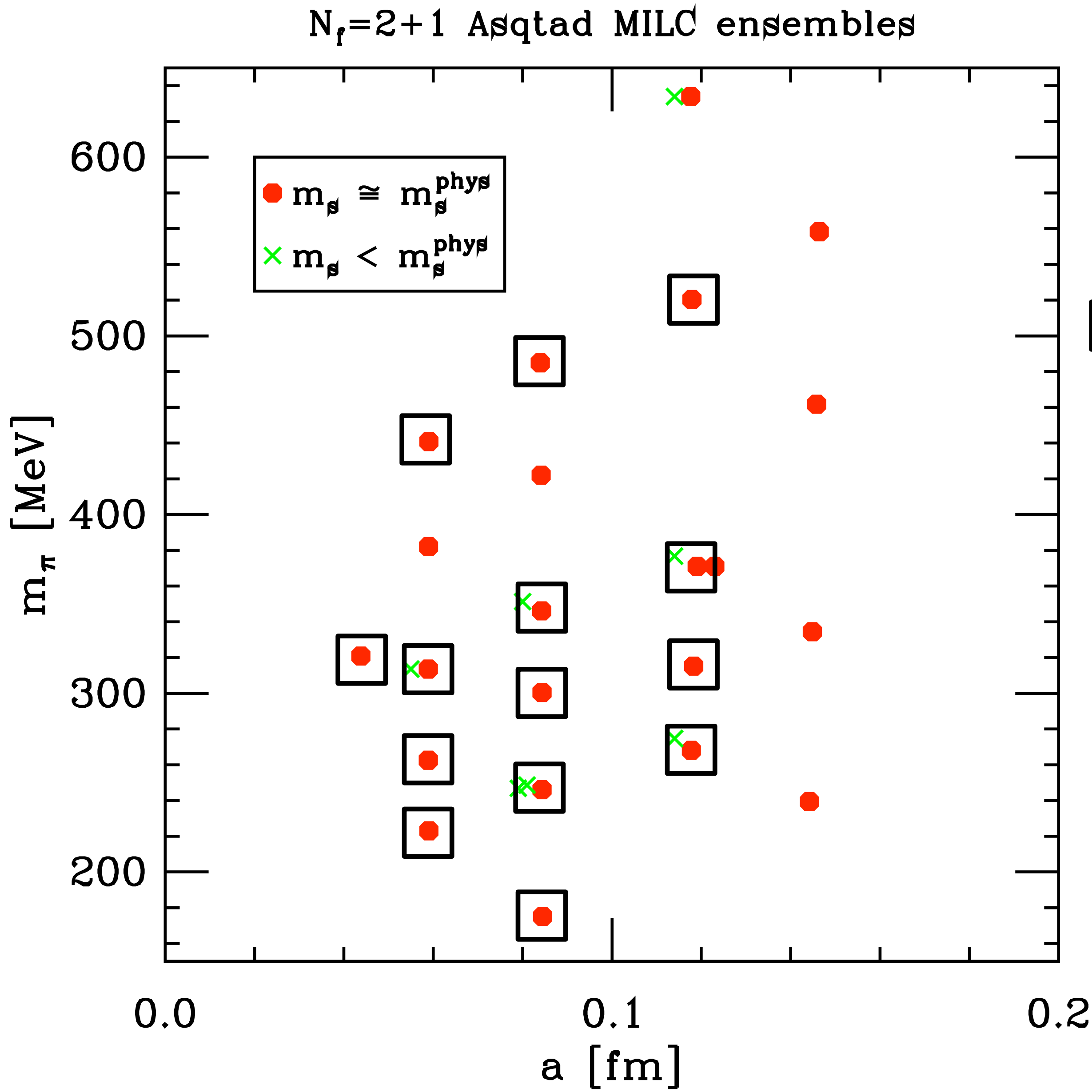

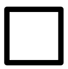

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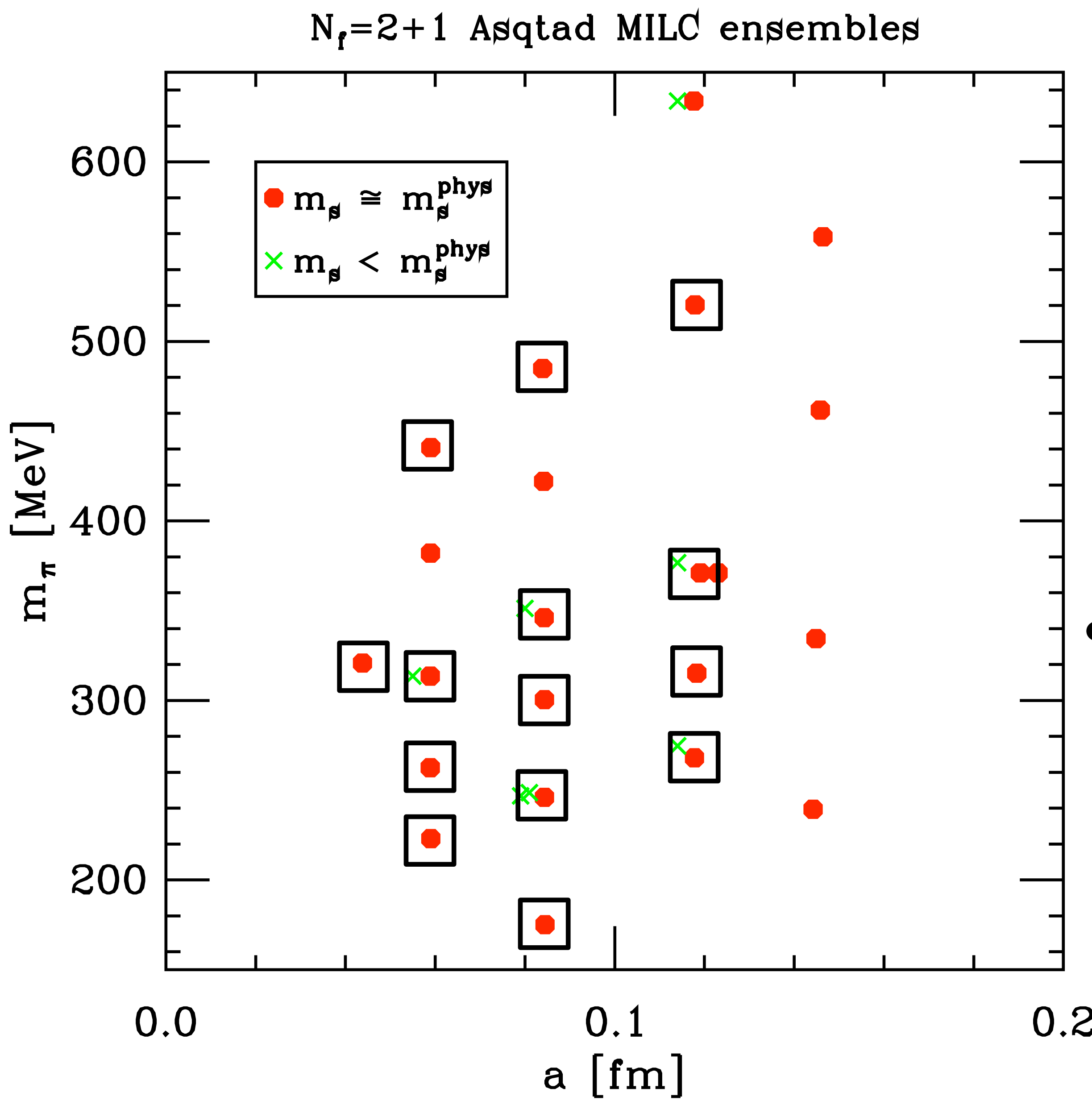

"new data" heavy-light decay const. analysis

- 0.06 fm and 0.045 ensembles added.

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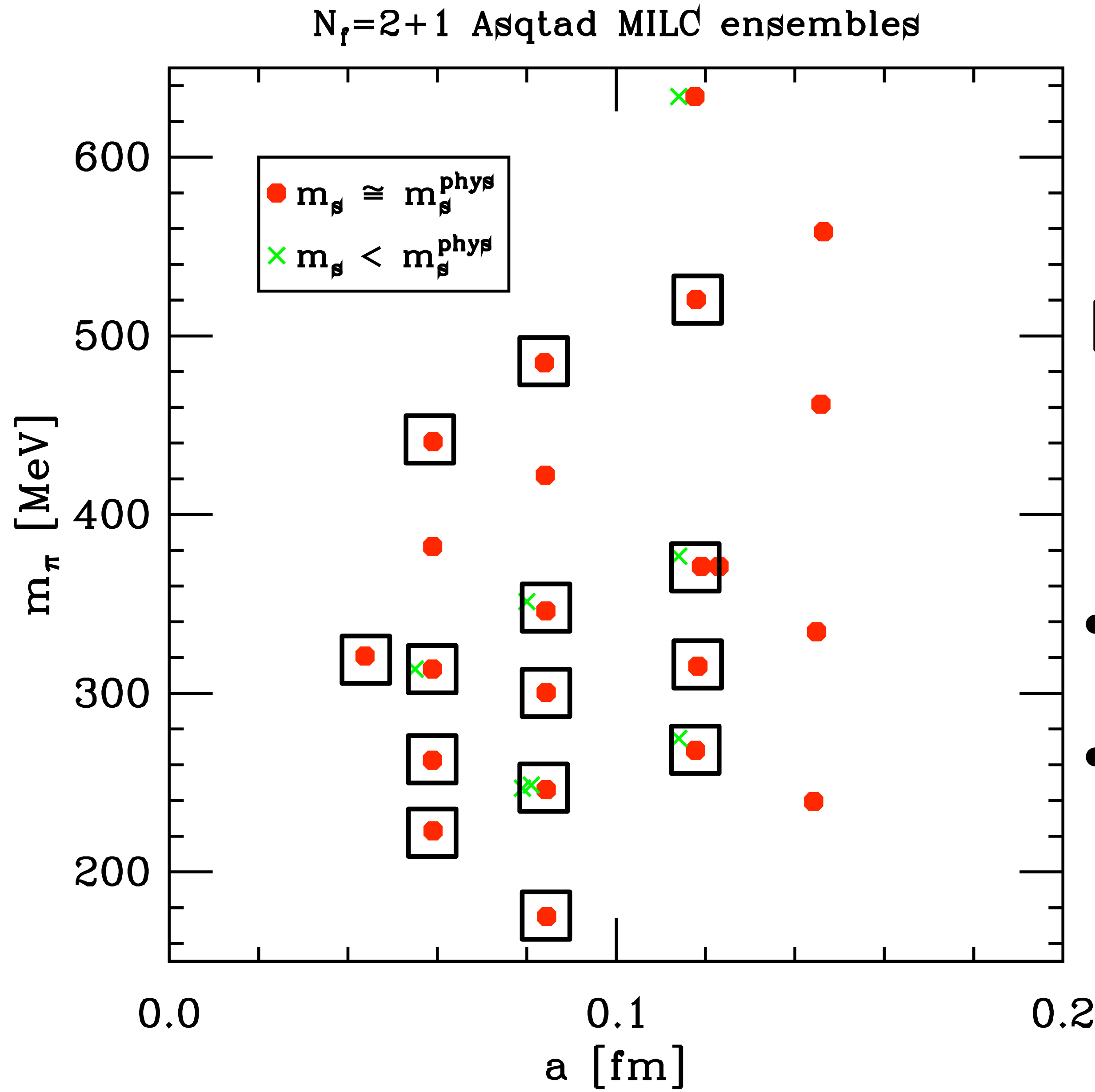
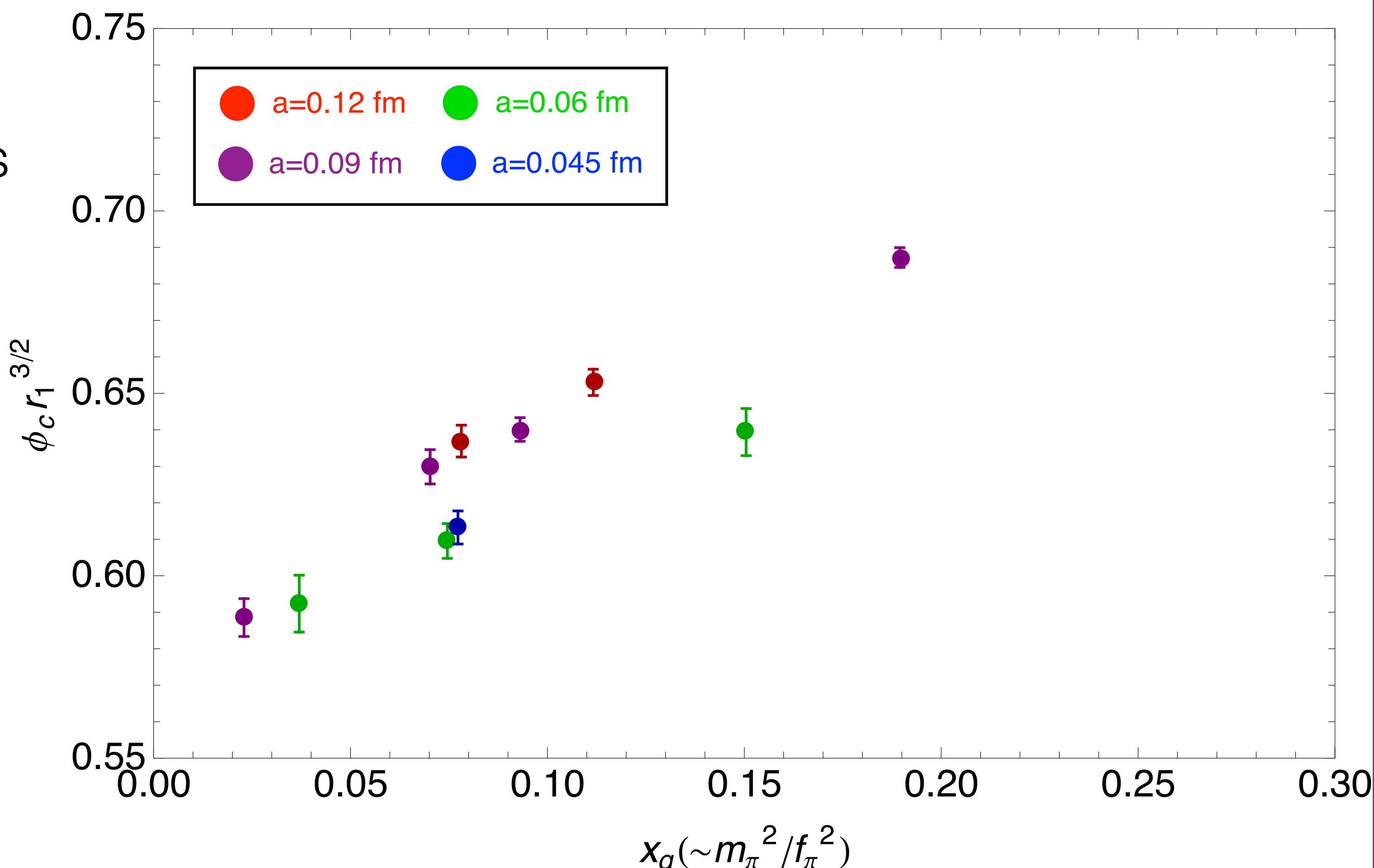


"new data" heavy-light decay const. analysis

- 0.06 fm and 0.045 ensembles added.
- runs lengthened by factor of ~2 to ~5.

“New Data” f_D

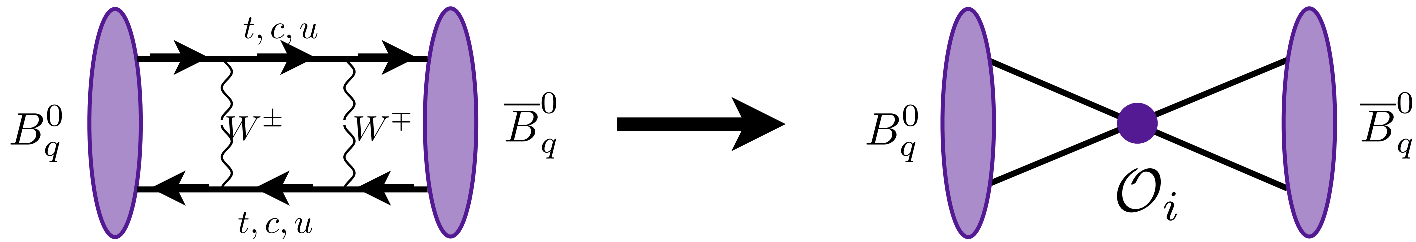
- statistical errors reduced as expected.
- correlator fits still need work; chiral fits are in progress.
- trend: f_D and f_{Ds} ↓ as a ↓



Outlook: Fermilab/MILC

	% Errors	
Quantity	"Old data" arXiv:1112.3051	"New data" (in progress)
f_{D_s}	4.2	2.2
f_D	5.2	2.8
f_{D_s}/f_D	2.1	1.1
f_{B_s}	3.9	2.6
f_B	4.5	2.8
f_{B_s}/f_B	2.1	1.2

B Mixing



$$\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} C_i \mathcal{O}_i$$

Operators are

SM

$$\mathcal{O}_1 = (\bar{b}^\alpha \gamma_\mu L q^\alpha)\,(\bar{b}^\beta \gamma_\mu L q^\beta)$$

$$\mathcal{O}_2 = (\bar{b}^\alpha L q^\alpha)\,(\bar{b}^\beta L q^\beta)$$

$$\mathcal{O}_3 = (\bar{b}^\alpha L q^\beta)\,(\bar{b}^\beta L q^\alpha)$$

BSM

$$\mathcal{O}_4 = (\bar{b}^\alpha L q^\alpha)\,(\bar{b}^\beta R q^\beta)$$

$$\mathcal{O}_5 = (\bar{b}^\alpha L q^\beta)\,(\bar{b}^\beta R q^\alpha)$$

Common parametrization

$$\langle \bar{B}_q^0 | \mathcal{O}_i(\mu) | B_q^0 \rangle \propto f_{B_q}^2 B_i(\mu)$$

B Mixing

- ✦ Fermilab heavy quarks with MILC 2+1 asqtad staggered light quarks
  - “Old data” project
    - 0.12 fm ≤ a ≤ 0.09 fm
    - focus on SM operators, and in particular on O_1, which gives

$$\xi = f_{B_s}\sqrt{\hat{B}_{B_s}} / f_{B_d}\sqrt{\hat{B}_{B_d}}$$

    - construct operators from Fermilab quark + naive quark (made from staggered).
      - drop NLO “wrong spin” terms [⇒systematic error estimate].
    - 1-loop perturbation theory for mixing.
    - to be posted in next month or so.
  - “New data” project: similar to above, but:
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    - complete set of SM and BSM operators.
    - all wrong spin terms included correctly in ChPT.
    - in progress.

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R.T. Evans,
E. Gámiz

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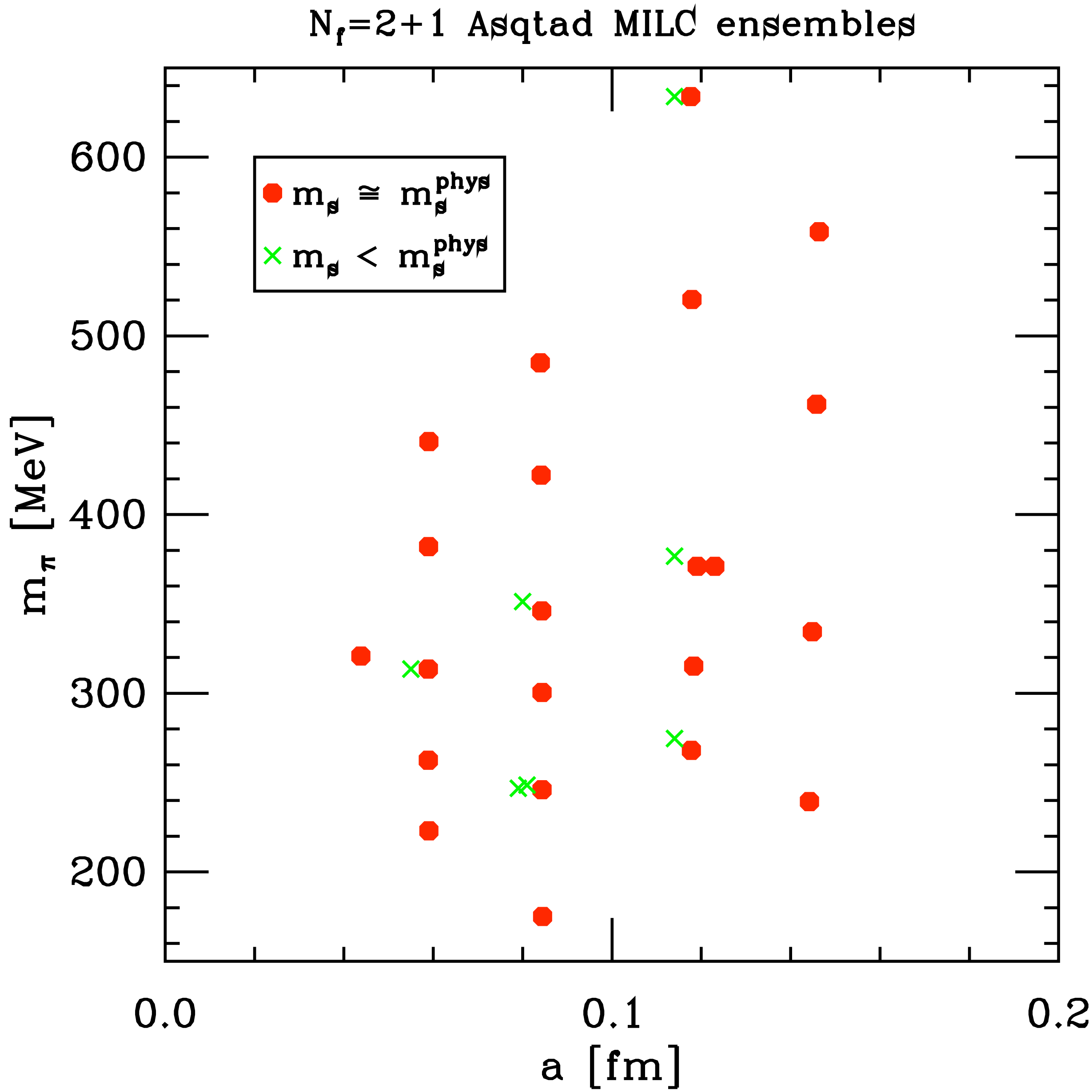

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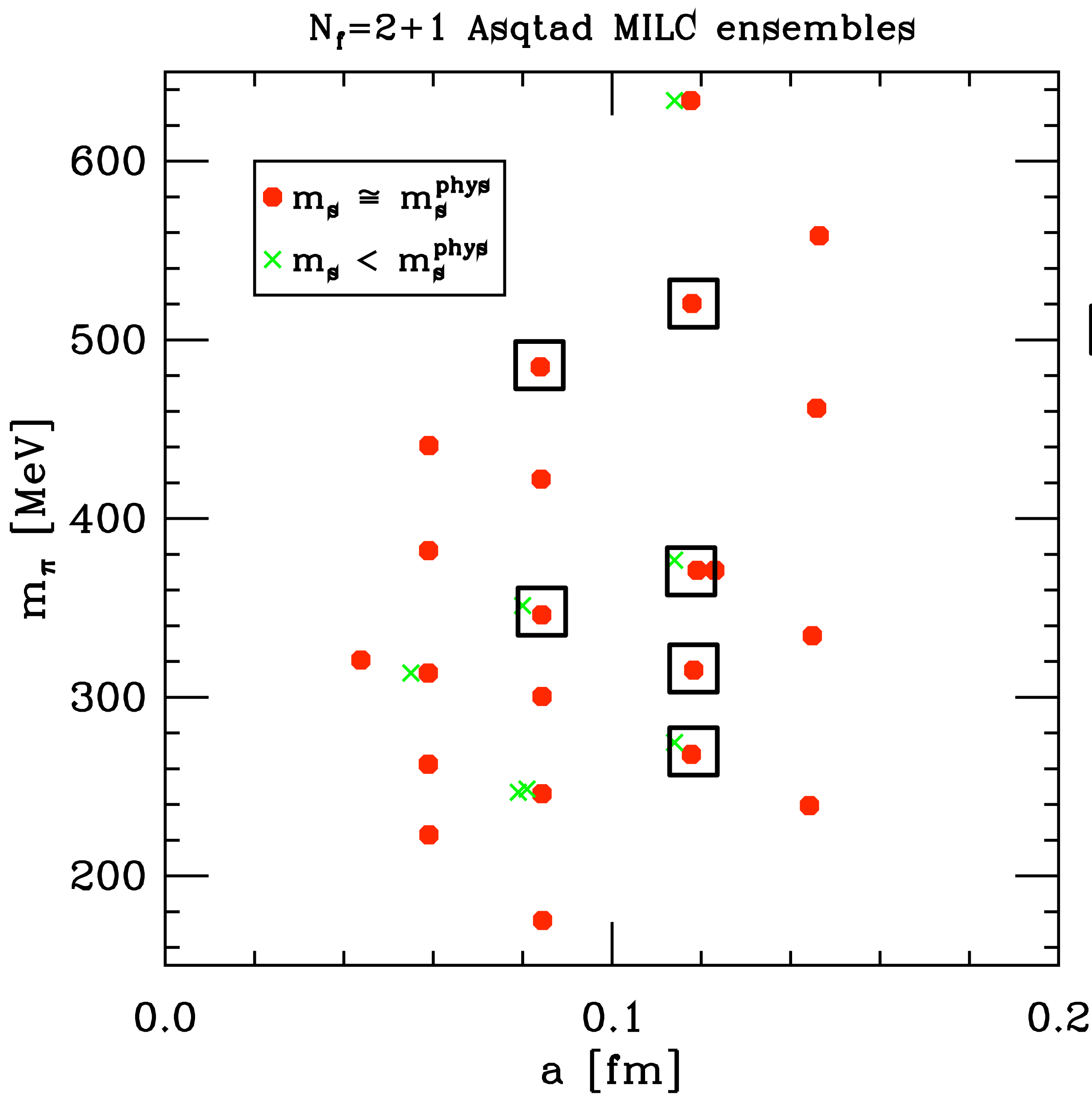


“old data” B-mixing analysis

“Wrong spin” Issue

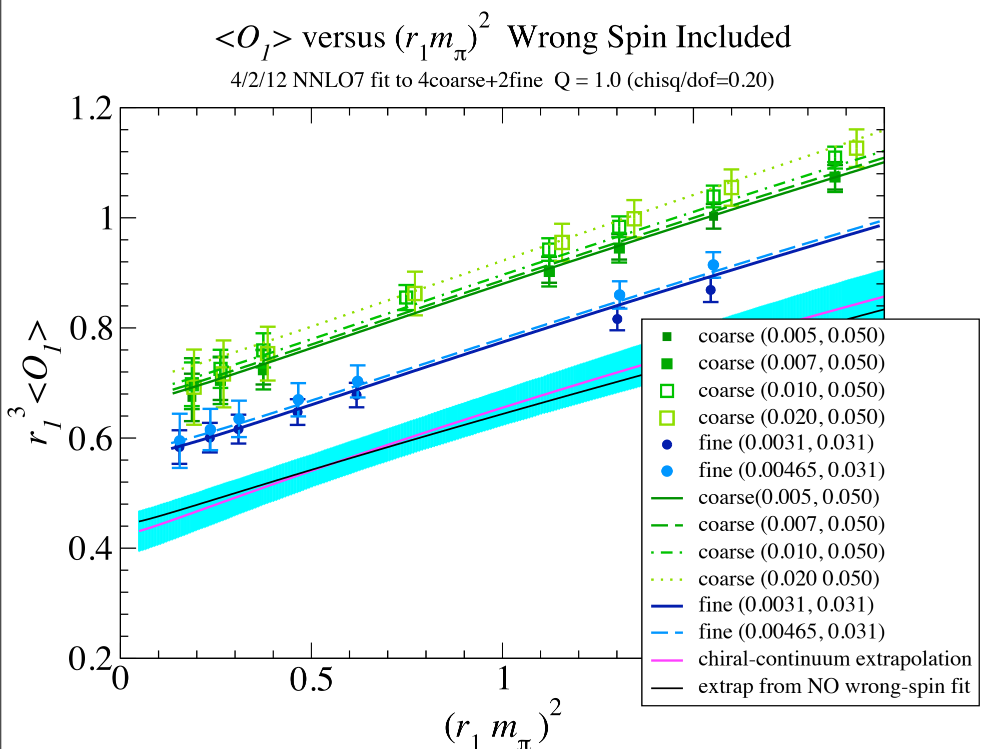
- Four quark operators as in [HPQCD, PRD 80 (’09)014503].
  - local products of bilinears of heavy quark fields $\bar{Q}(x)$ and naive quarks $\Psi(x)$ (made from staggered):

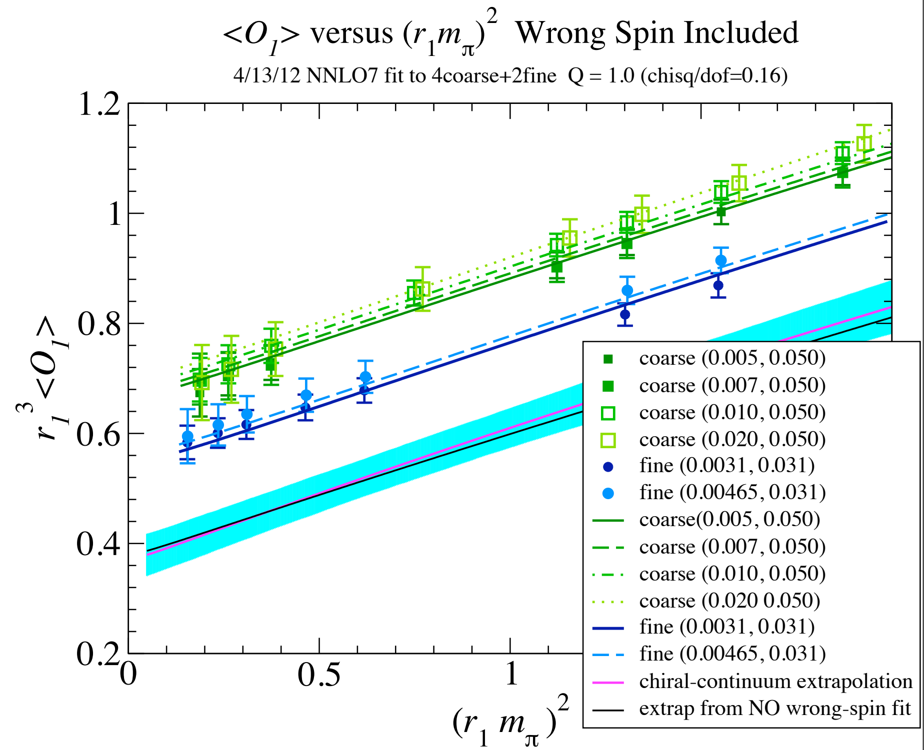
$$\bar{Q}(x)\Gamma\Psi(x)\ \bar{Q}(x)\Gamma'\Psi(x)$$

- Desired spin-taste of staggered quarks not constructed by separately summing each bilinear over hypercube $\Rightarrow$ contributions from unwanted spin-tastes.
  - vanish in continuum limit by taste conservation.
  - but will appear in staggered ChPT at some order.
  - we had an argument (in a collaboration note) that chiral logs from wrong-spin taste first appear at NNLO. [Was used in HPQCD paper.]
  - in writing up our B mixing computation, found flaw in previous argument: such terms appear at NLO and need to be included.

“Wrong-spin” and Chiral/Continuum Errors

- Effects of wrong spin ops have now been calculated to 1-loop in staggered ChPT [CB].
  - don’t have all needed matrix elements in old-data calc, but can estimate effect by sample new-data calc.





  - wrong-spin contrib < stat + other chiral/continuum errors, but effect on slope seems significant $\Rightarrow$ tends to increase ξ .

Final “Old-Data” Results

TABLE IX. Complete error budget and total error for the B^0 mixing parameter ξ. All errors are given in %.

Source of uncertainty	Error (%)
Statistics $\oplus$ light-quark disc. $\oplus$ chiral extrapolation	3.7
Mixing with wrong-spin operators	3.2
Heavy-quark discretization	0.3
Scale uncertainty (r_1)	0.2
$g_{BB^*\pi}$	0.7
Light-quark masses	0.5
One-loop matching	0.5
Tuning κ_b	0.4
Finite volume	0.1
Mistuned coarse u_0	0.1
Total Error	5.0

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Result: $\xi = 1.268(63)$ (nearly final)

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C. Bouchard, E. Freeland

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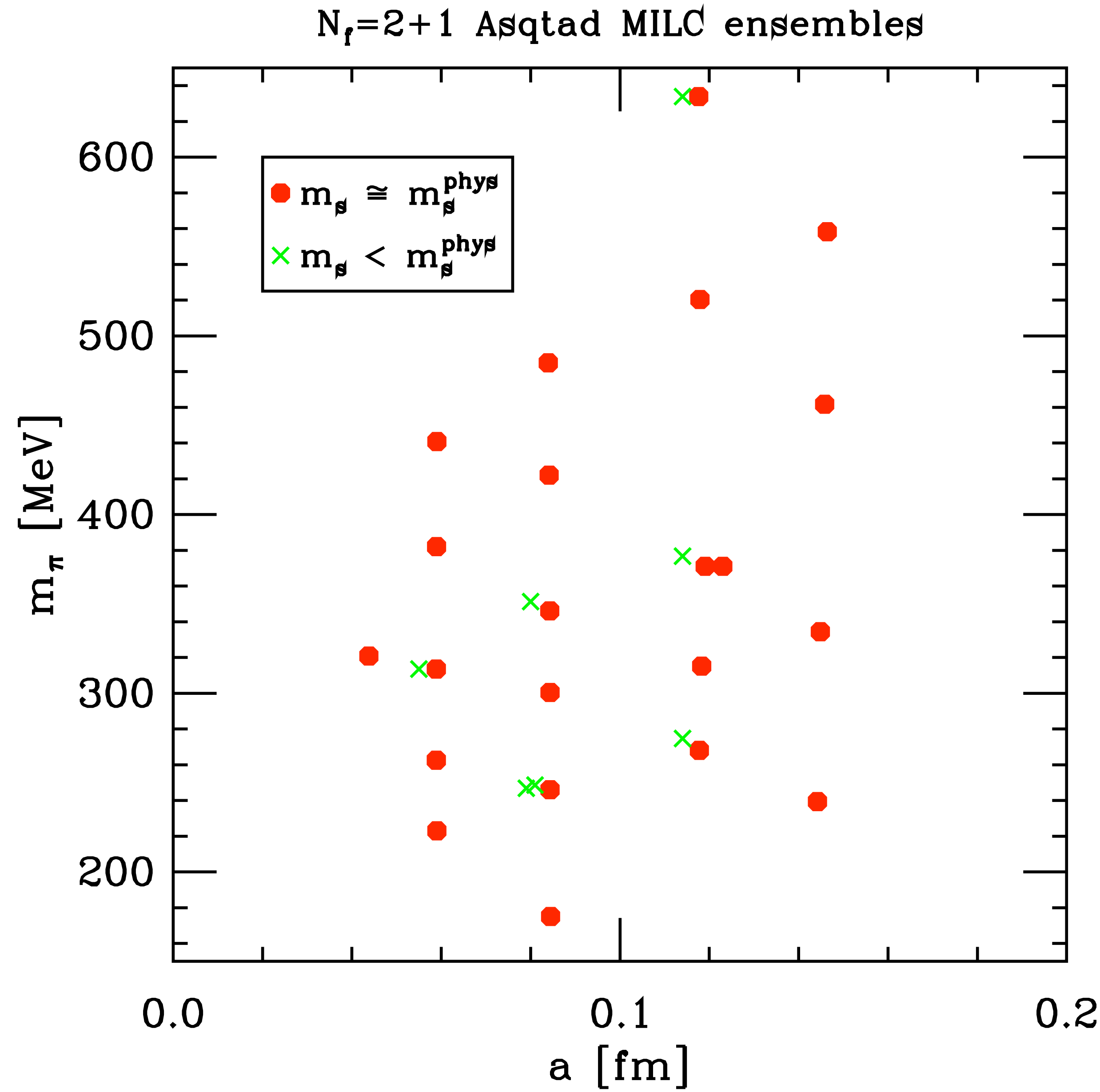

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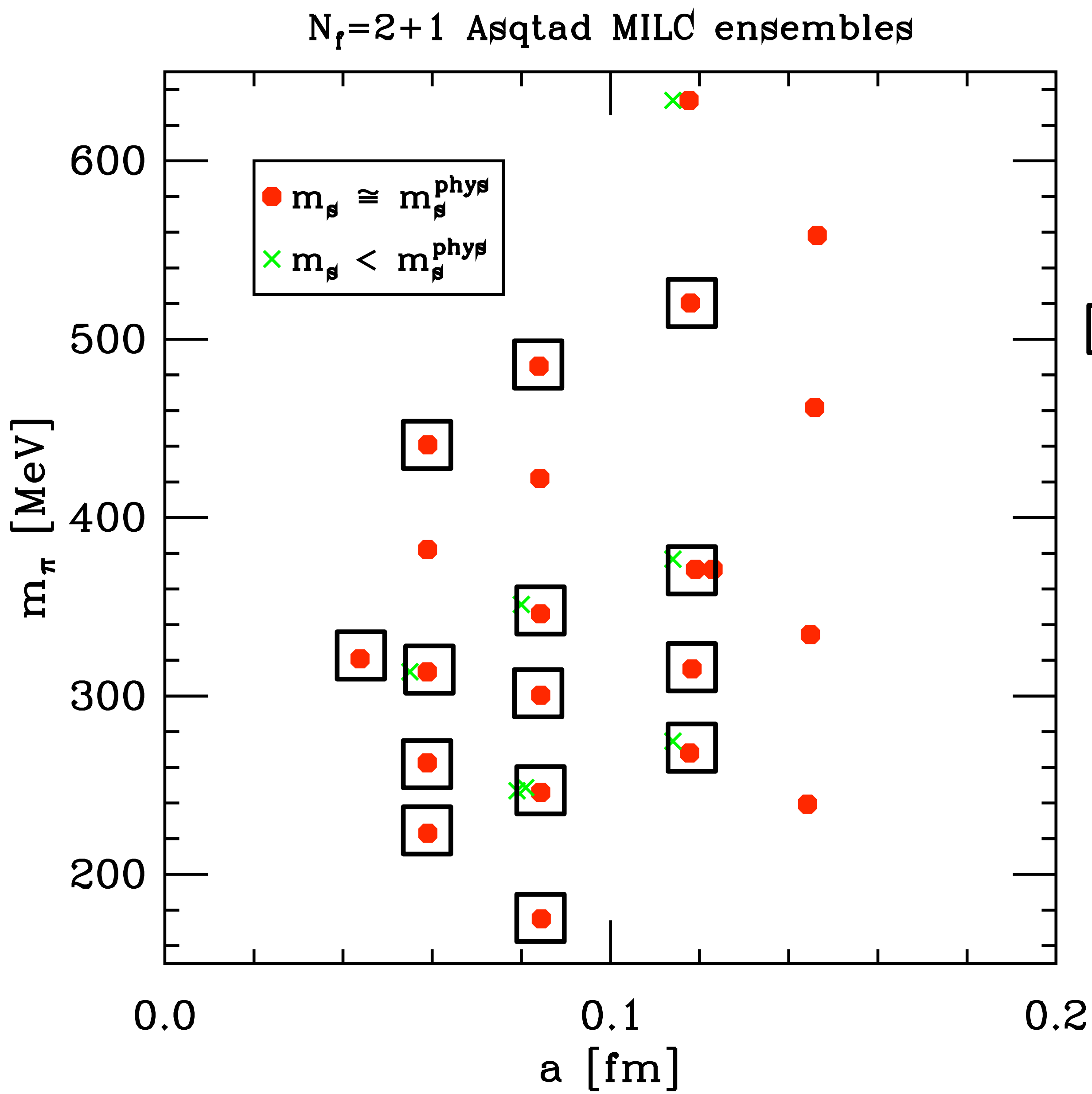

"new-data" B-mixing: plan

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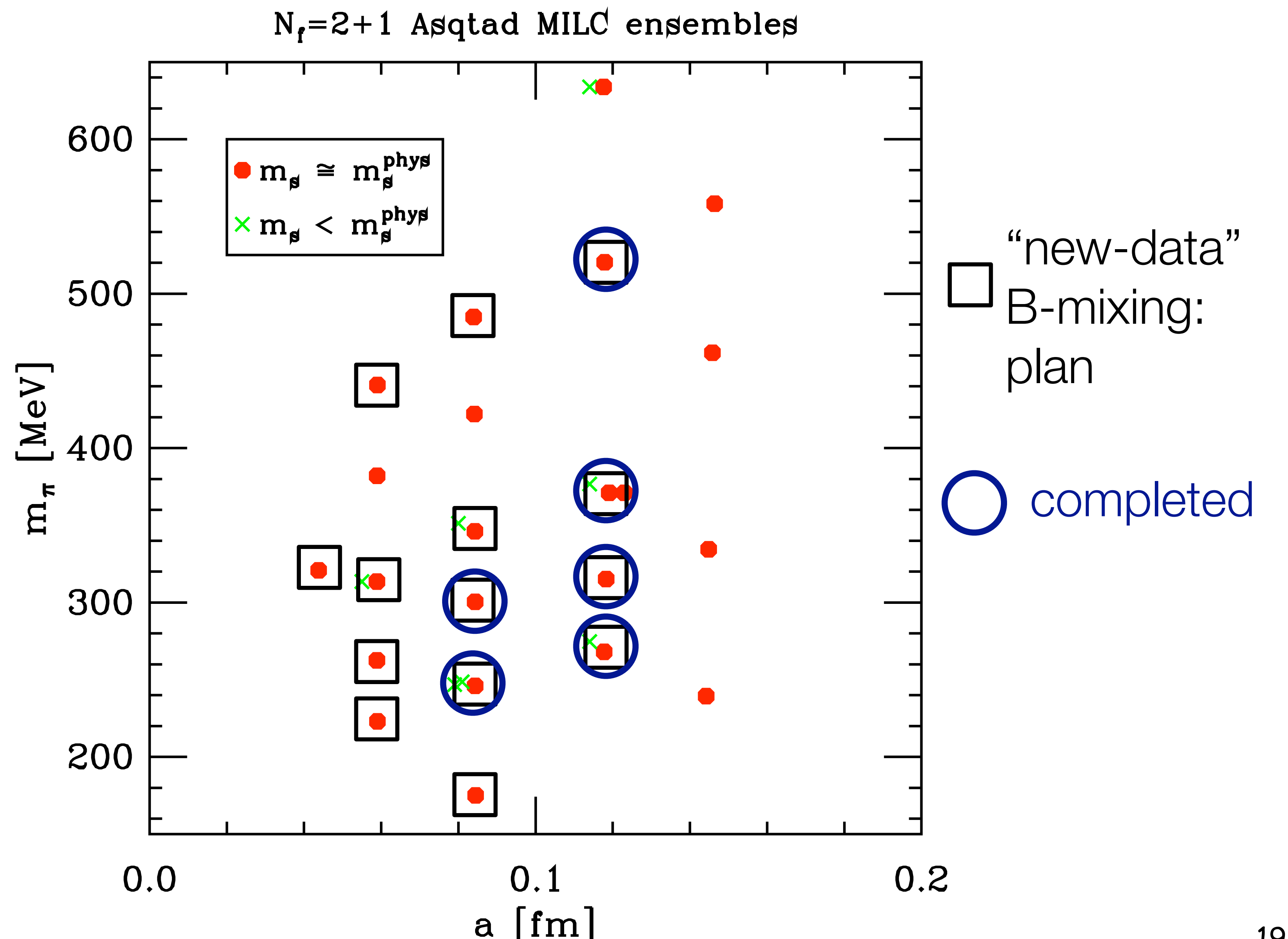

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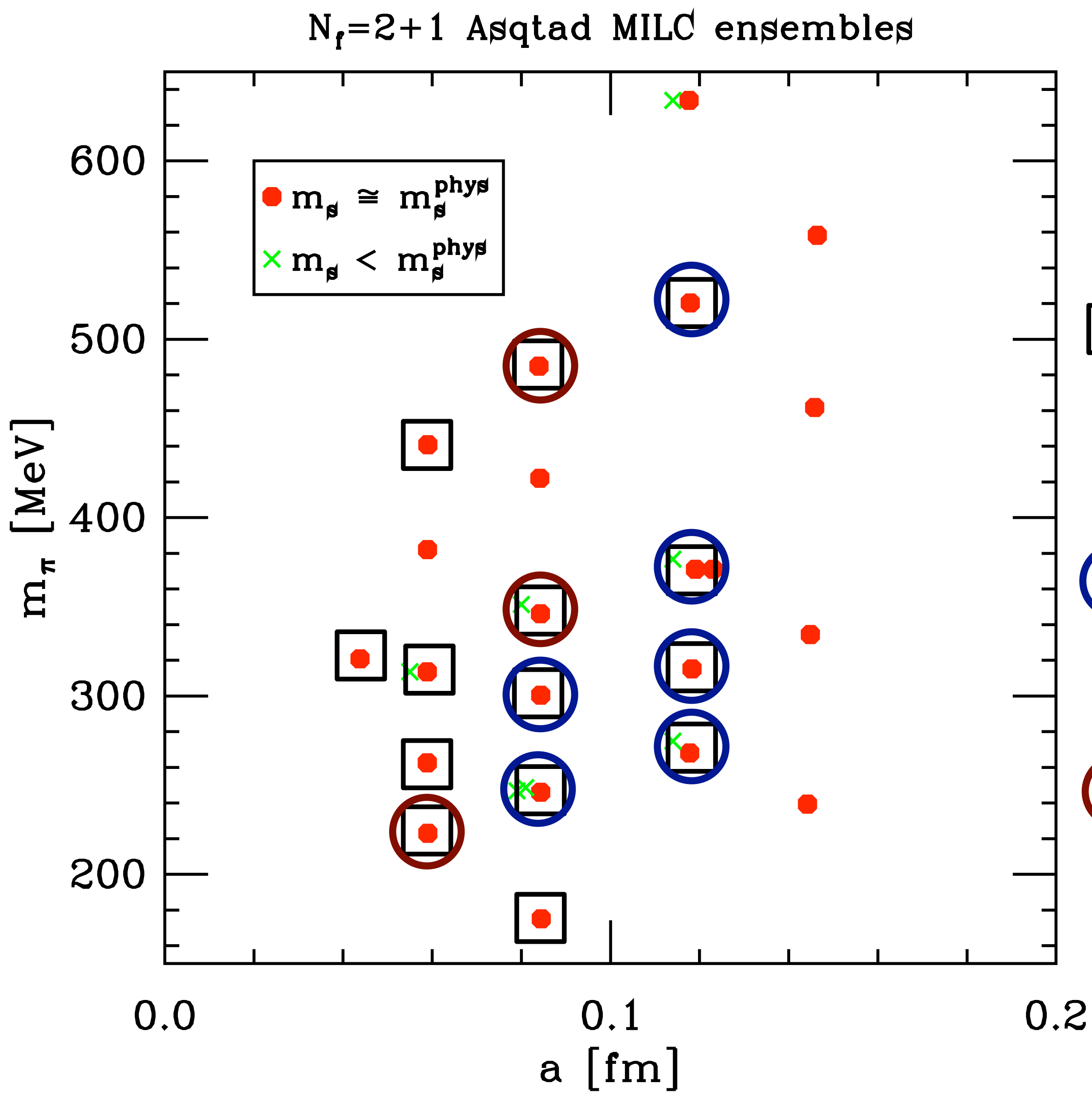
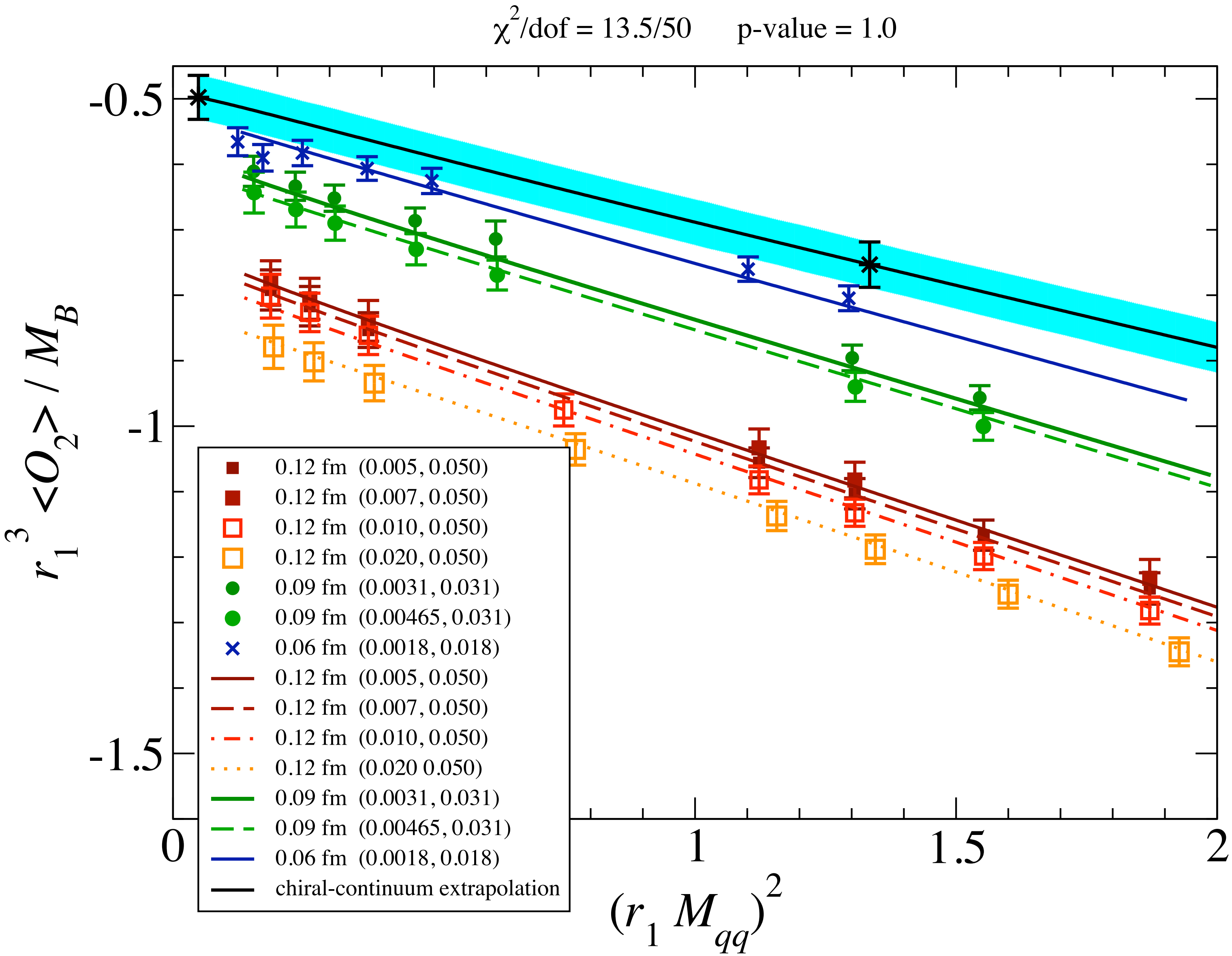


"new-data" B-mixing: plan

completed

subset of operators done

Matrix element of O_2



(needed in SM for ΔM and $\Delta\Gamma$; also BSM)

Anticipated Error Budget

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- Snapshot of statistical and chiral-continuum extrap errors at current state of running:

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B_d^0	statistical	8.6	6.8	16	4.3	5.5
	chiral-continuum systematic	12	11	3.3	0.2	4.4
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- ✦ Some other expected errors:

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heavy-quark discretization	4
one-loop matching	8
finite-volume effects	1
subtotal	10

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  - may be able to reduce a bit (to ~6%?) with finer spacings.

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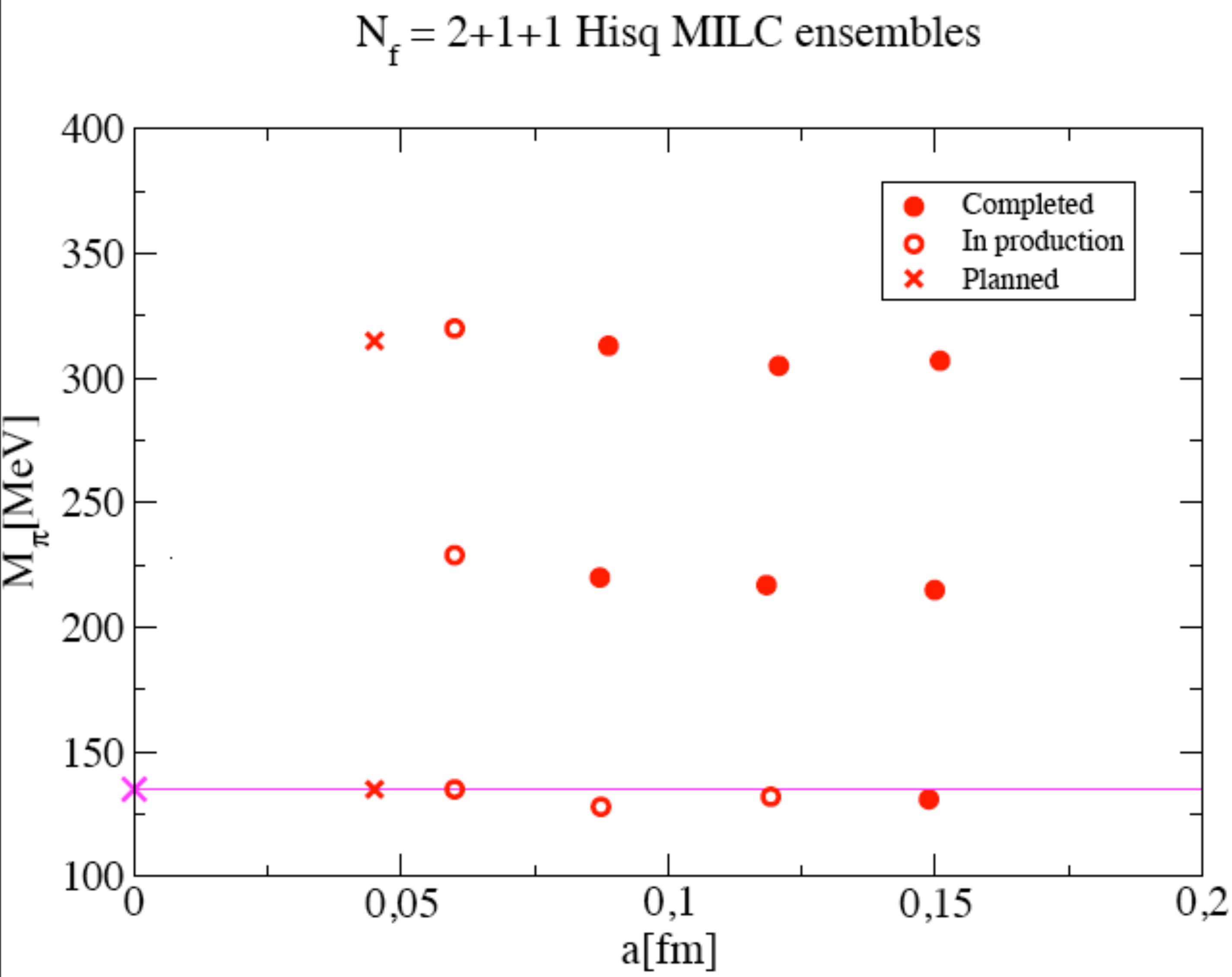
MILC HISQ 2+1+1 Ensembles

- ✦ Asqtad ensembles are complete; though there is more physics still to extract.
- ✦ For higher precision, have moved to HISQ [Follana et al. [HPQCD], PRD 75 (2007) 054502].
  - Reduced $O(\alpha_S a^2)$ and $O(\alpha_S^2 a^2)$ errors with respect to Asqtad.
  - $(am_c)^4$ errors reduced ⇒ treat charm with same relativistic action as light quarks.
  - Ensembles include charm sea quarks
    - (although error of quenching charm is probably negligible in most cases, it doesn't cost much to include it in sea.)

[A. Bazavov, D. Toussaint]

HISQ Ensembles



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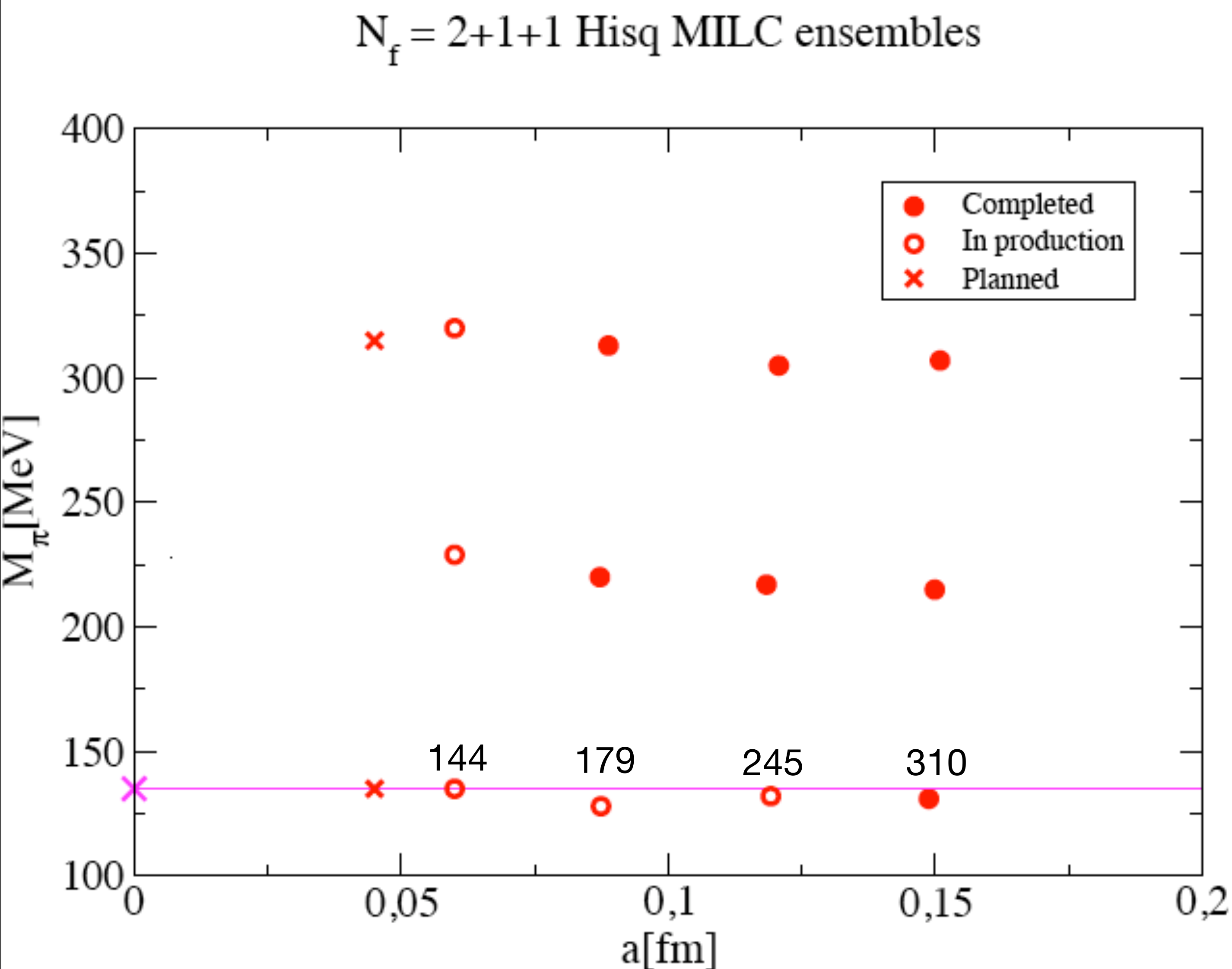

$m_\pi^{\rm RMS}$ [MeV]

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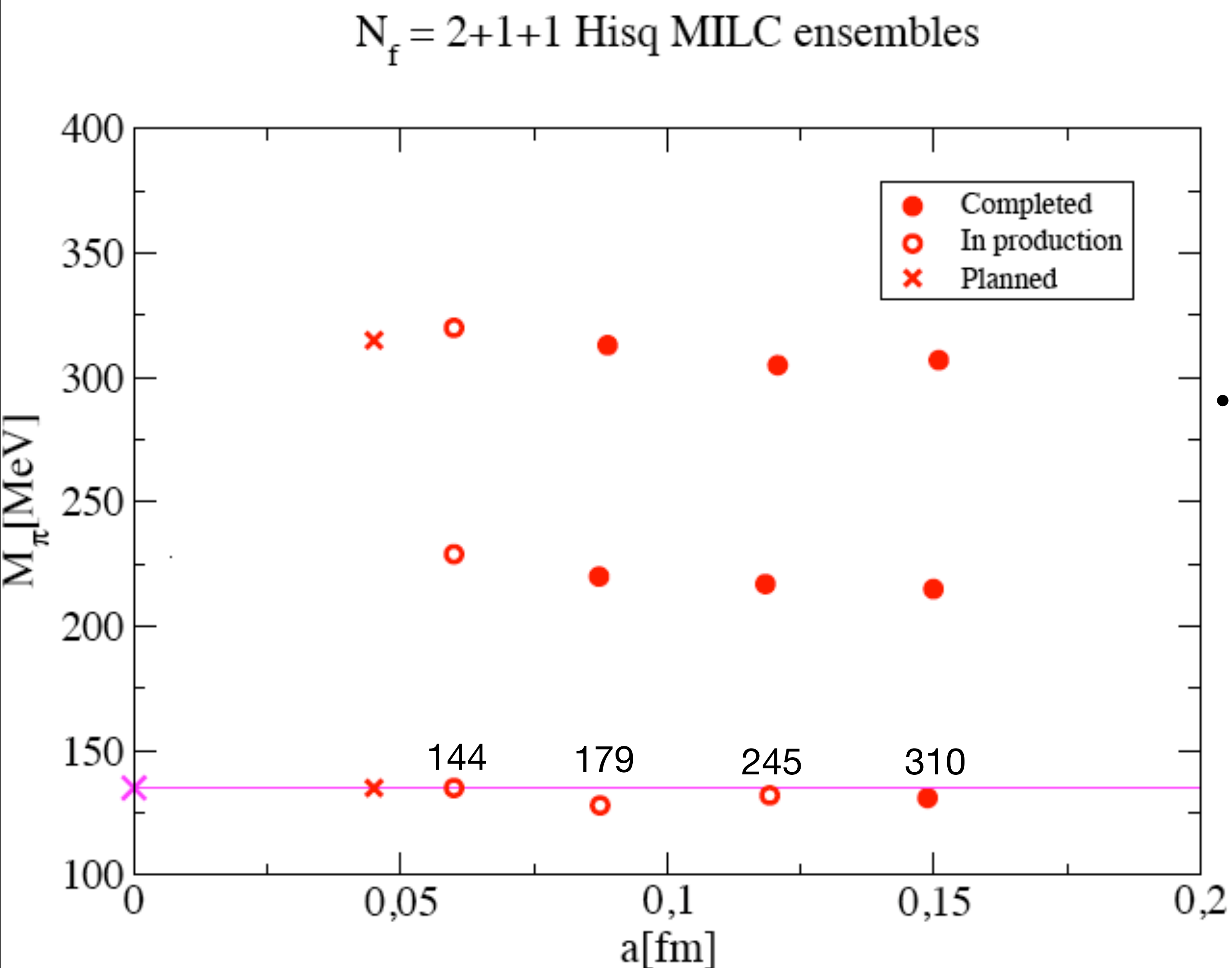
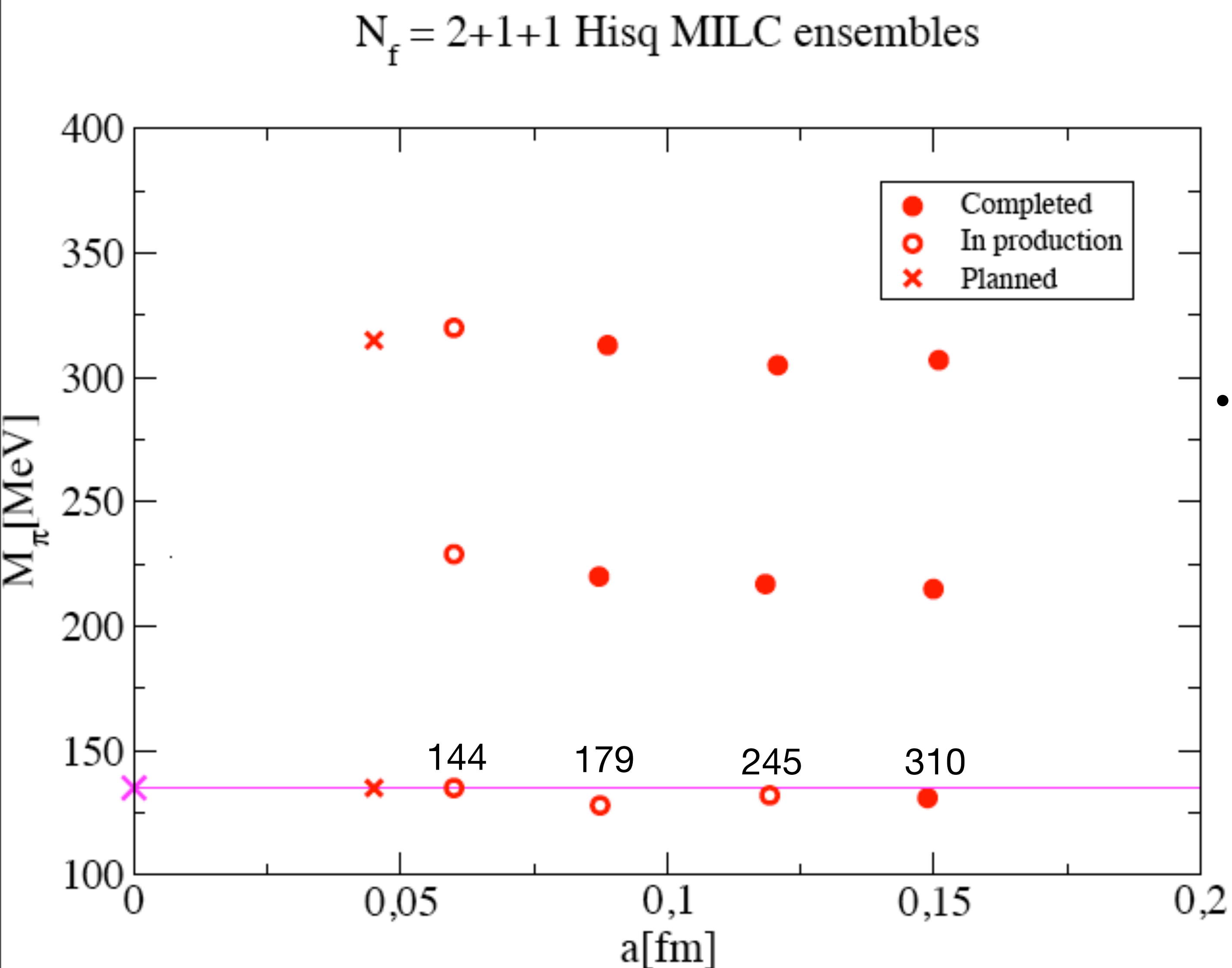


m_π^{RMS} [MeV]

- recall that coupling of these sea pions to valence pions is NLO in ChPT.

HISQ Ensembles



m_π^{RMS} [MeV]

- recall that coupling of these sea pions to valence pions is NLO in ChPT.

$\Rightarrow$ suppressed by $\dfrac{(m_\pi^{\mathrm{RMS}})^2}{16\pi^2 f_\pi^2}$

Light decay constants w/ 2+1+1 HISQ

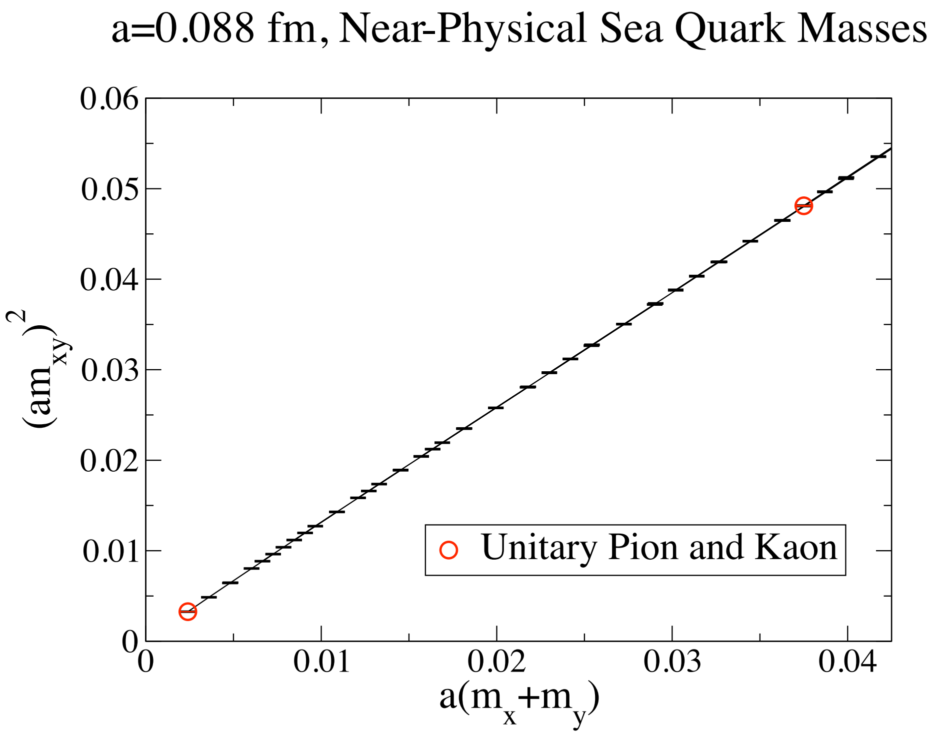
- In Asqtad case, needed ensembles with m_s lighter than physical to control SU(3) chiral extrapolation.
- In HISQ case, such ensembles have not been available (but are coming on line now...), so SU(3) fits have not yet been very successful.
- "Heavy kaon" SU(2) chiral perturbation theory [*à la* RBC/UKQCD and PACS-CS], has been recently worked out for staggered case [CB, Du, and Lightman], but not yet tried.
- So focus for now on physical-mass HISQ ensembles, where ChPT not needed.

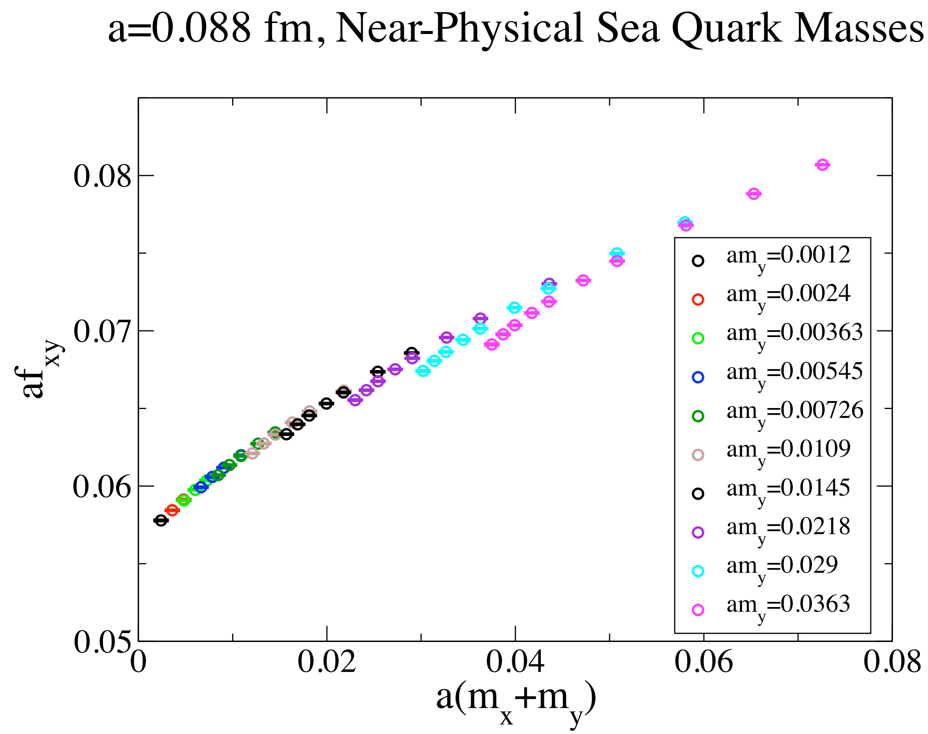
[M. Lightman]

HISQ f_π , f_K

✦ On each ensemble:

- for valence masses m_x, $m_y \lesssim m_s$, meson mass squared $(m_{xy})^2$ is very linear in $m_x + m_y$.
- decay const f_{xy} appears linear for $m_x + m_y \lesssim 0.5\, m_s$, but there is separate dependence on m_x and m_y for heavier masses.





HISQ f_π , f_K

- Suggests following interpolating forms:

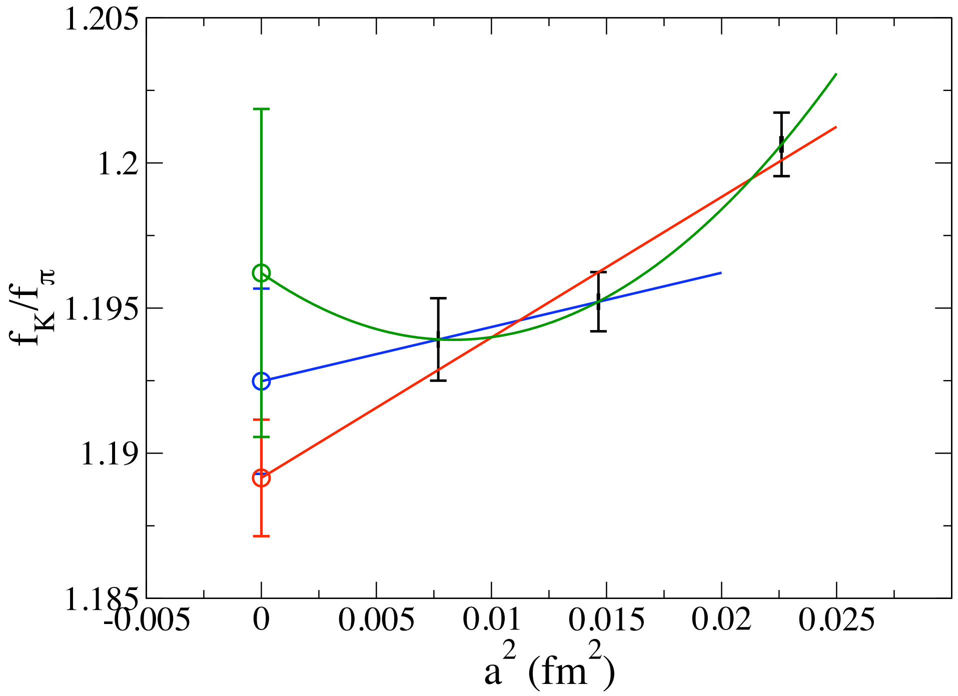
$$
\begin{aligned}
(am_{xy})^2 &= A_1 + B_1(am_x + am_y) \\
af_{xy} &= \begin{cases} A_2 + B_2(am_x + am_y), & \text{for } m_x \sim m_l \text{ and } m_y \sim m_l \\ A_3 + B_3 am_x + C_3 am_y, & \text{for } m_x \sim m_l \text{ and } m_y \sim m_s \end{cases}
\end{aligned}
$$

- On each ensemble, do linear interpolations of this form between $(m_x, m_y) = (m_l, m_l)$ and its nearest neighbor, and between $(m_x, m_y) = (m_l, m_s)$ and its nearest neighbors.
- Require that $(f_{xx}/m_{xx})^2 = (f_\pi/m_\pi)^2$, solve for m_x to determine physical light mass m_l^{phys}
  - (Checked that quadratic interpolation with 3 points makes little difference)
- Require that $(m_{xy}/m_{xx})^2 = (m_K/m_\pi)^2$, solve for m_y to determine physical strange mass m_s^{phys}
  - (Checked that interpolating $2(m_{xy})^2$-$(m_{xx})^2$ to find m_s^{phys} with makes little difference)

HISQ f_π , f_K

✦ Then linearly interpolate f and f to physical masses.

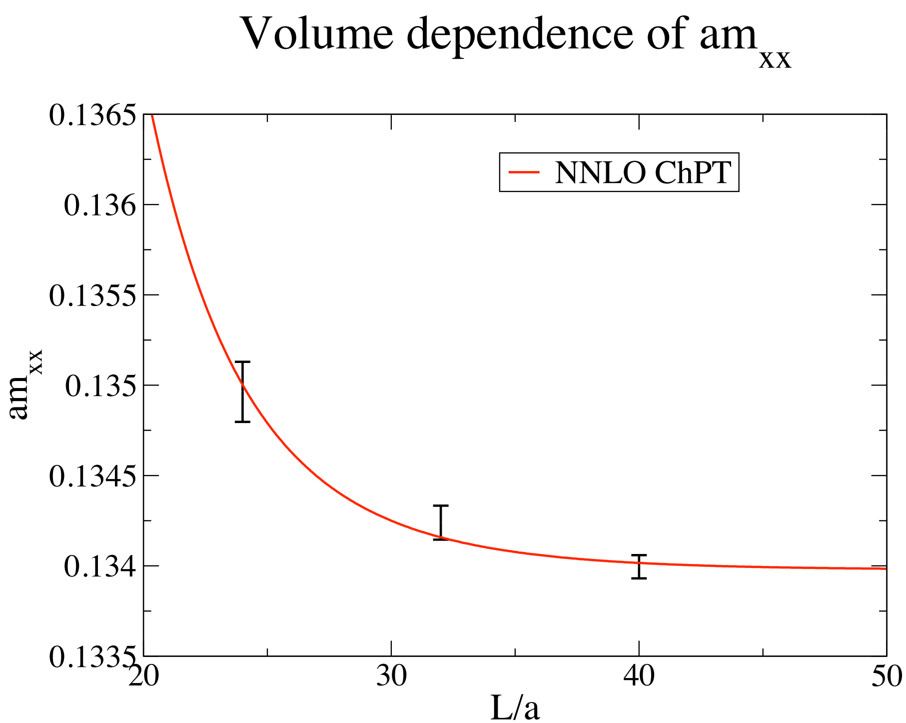
- for the moment focus on f_K/f_π ; compute it for each ensemble.
- then fit it as function of a^2.

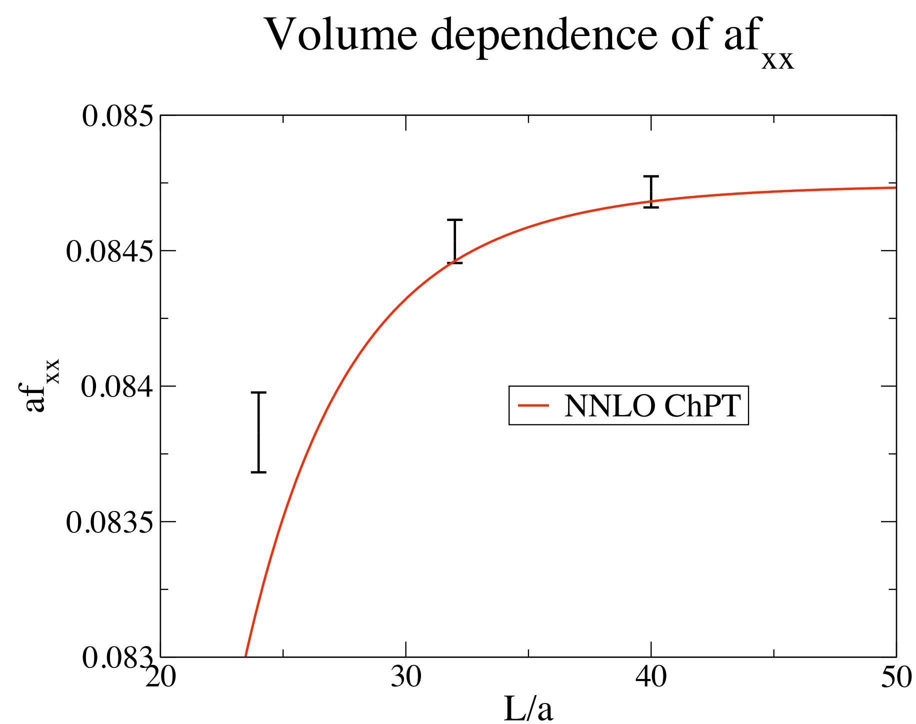


- two finest points in linear fit: $(f_K/f_\pi)_{continuum} = 1.1925(32)$
- all 3 points in linear fit: $(f_K/f_\pi)_{continuum} = 1.1892(20)$
- parabola through all 3 points: $(f_K/f_\pi)_{continuum} = 1.1962(56)$

HISQ f_π , f_K: systematic errors

- ✦ Half the largest difference between continuum extraps to estimate that error.
- ✦ Finite volume effects from ensembles with L=24, 32, and 40 with a=0.12 fm and m_l = 0.1 m_s.





- "NNLO ChPT" means using Colangelo, Dürr, Haefeli, NPB 721 ('05) 136] to terms of $\mathcal{O}([m_\pi^2/16\pi^2 f^2]^2)$.

HISQ f_π , f_K: preliminary result

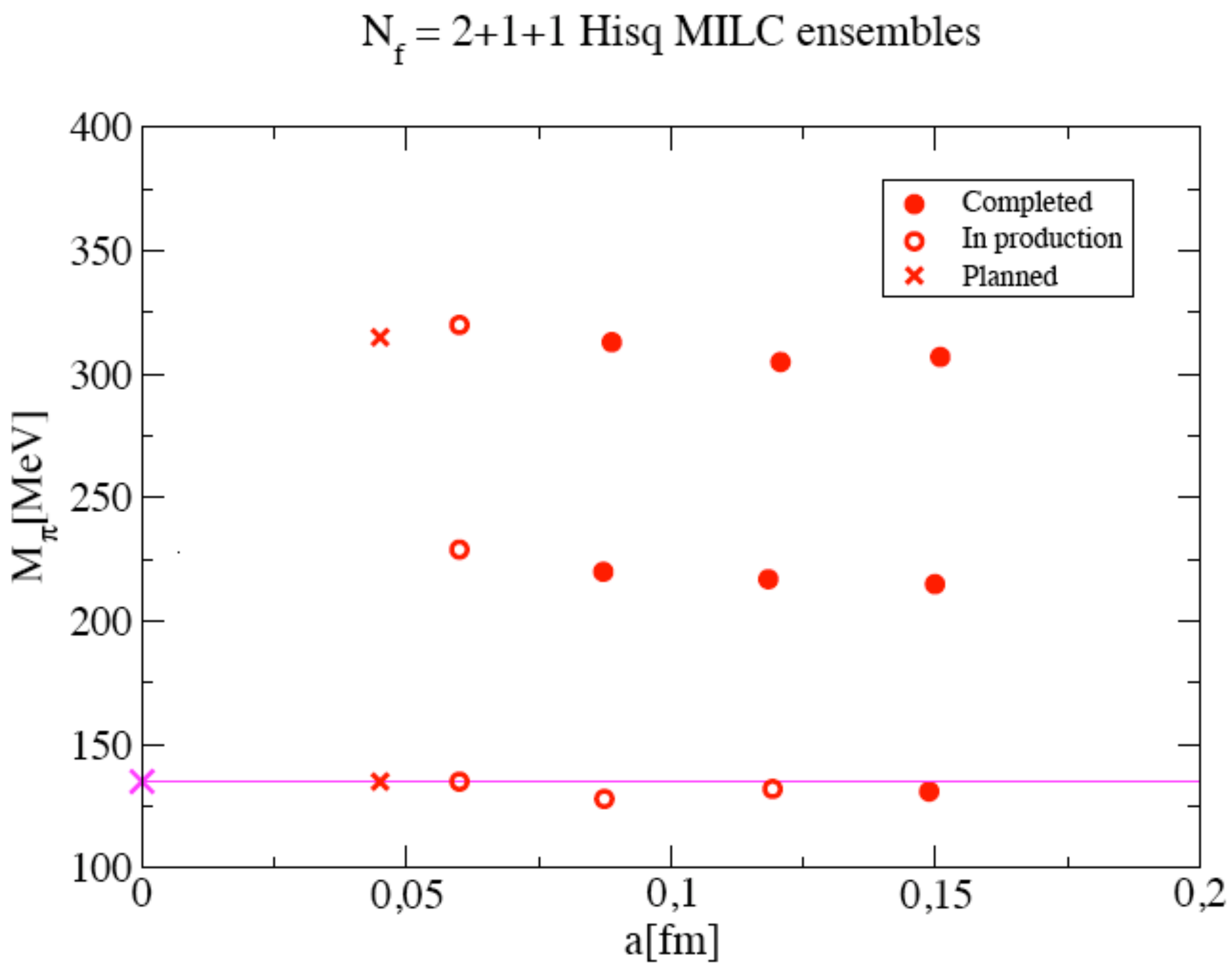
- Find: $f_K/f_\pi = 1.1925(32)_{\rm stat}(36)_{\rm continuum}(32)_{\rm finite\ volume}$
- Effect still to investigate: tuning error in sea quark masses.
- More study of interpolating fits also needed.
  - A systematic way will be to use the SU(2) staggered ChPT; will also allow us to get information out of the ensembles with u,d mass heavier than physical, and find LECs.
  - Some ensembles with m_s lighter than physical have recently been completed; SU(3) fits should now also be possible.

D decay constants w/ 2+1+1 HISQ

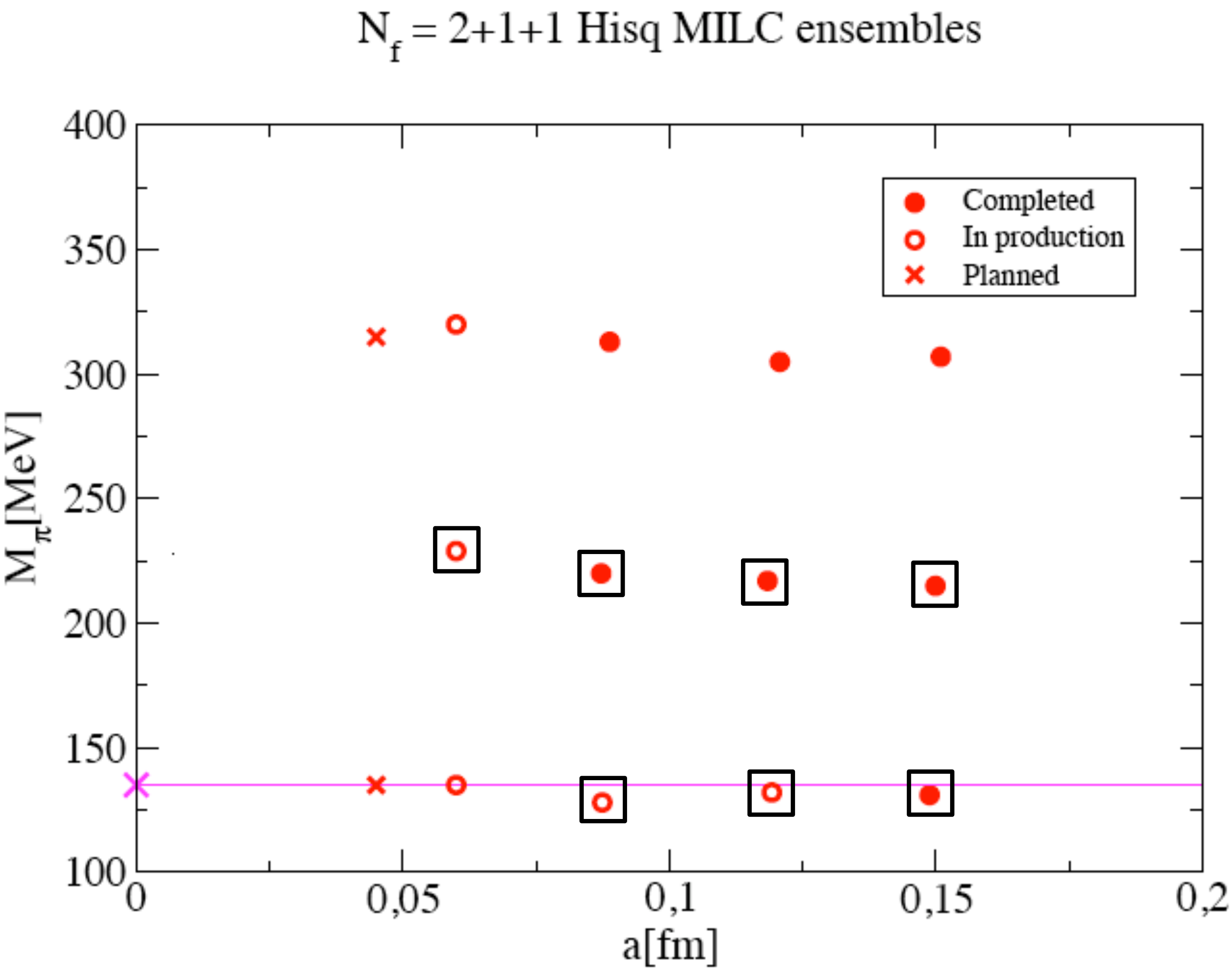
- ✦ advantage of HISQ: discretization errors sufficiently reduced (both a^2 and $(ma)^4$) that charm may be treated with same action as light quarks.
  - avoid renormalization errors and many tuning issues.
  - shares to some degree the small statistical errors of staggered light pseudoscalars.

[D. Toussaint, J. Kim]

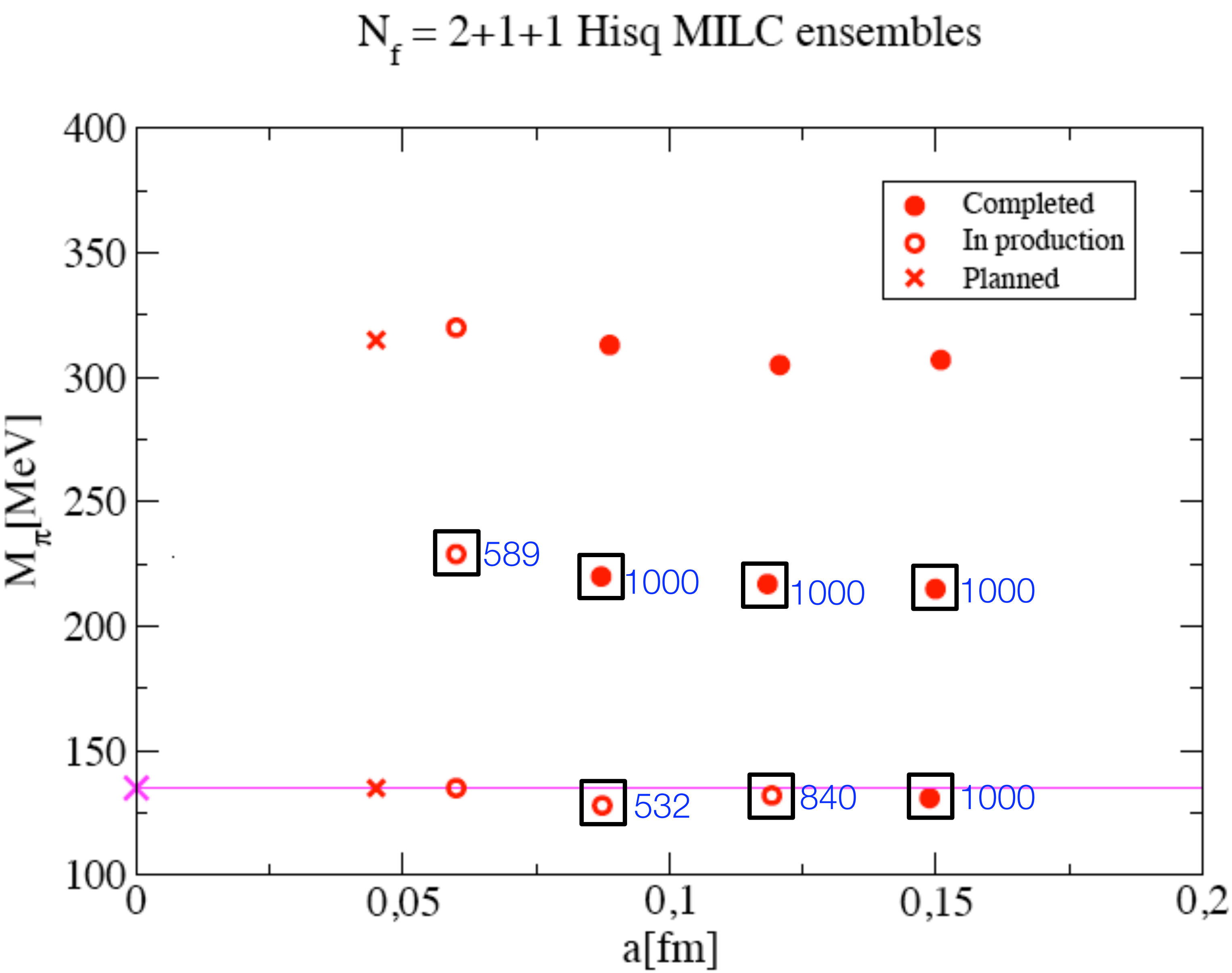
HISQ Ensembles



HISQ Ensembles



HISQ Ensembles



f_D project

configs.

f_D , f_{Ds} procedure

✦ On each ensemble:

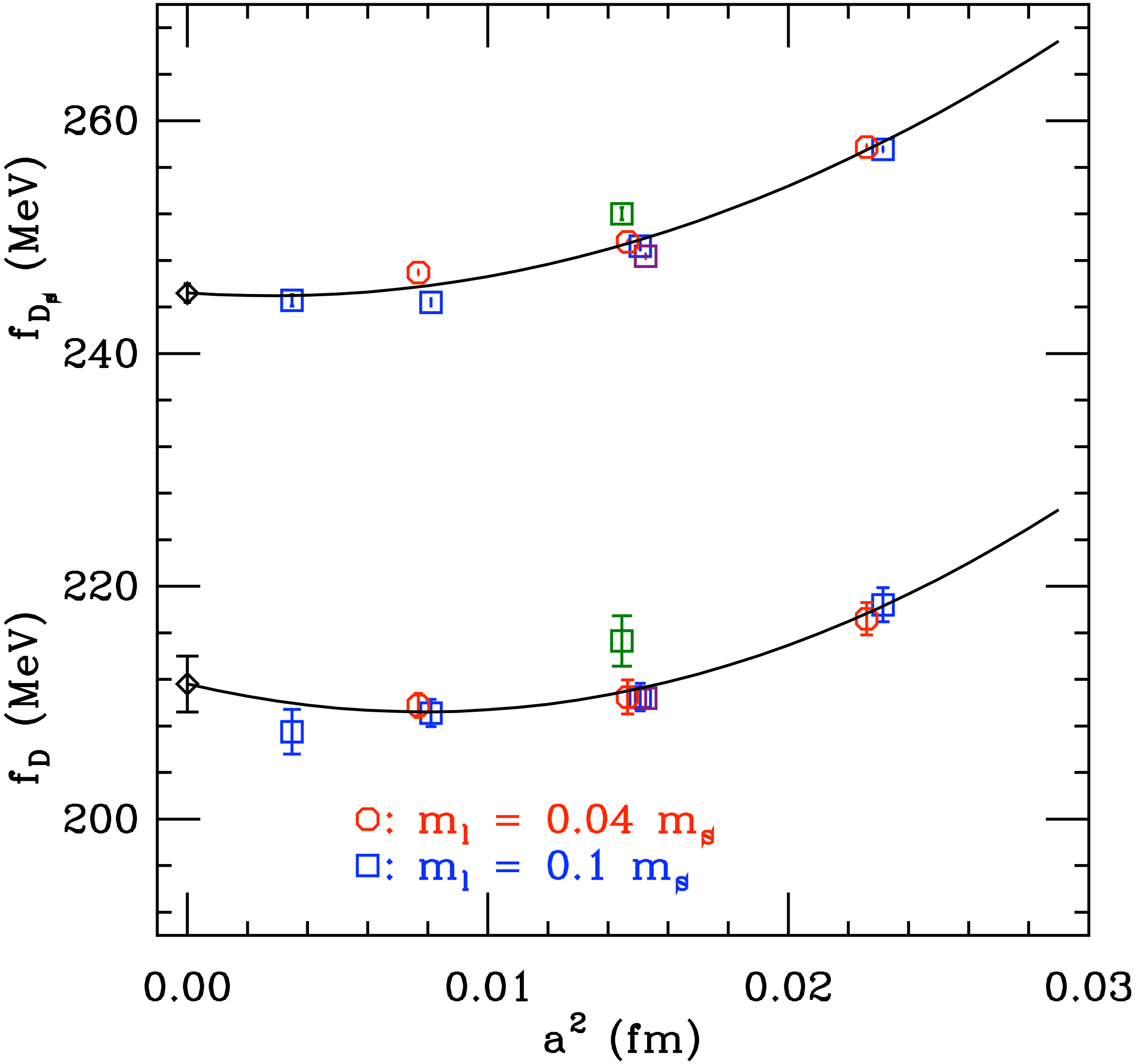
- $(M_\pi/f_\pi)^2 \longrightarrow am_{u,d}^{\text{phys}}$, and then $\longrightarrow a$
  (cubic interpolation through 3 light valence masses)

- $2M_K^2 - M_\pi \longrightarrow am_s^{\text{phys}}$
  (linear interpolation/extrapolation through 2 strange valence masses)

- $M_{D_s} \longrightarrow am_c^{\text{phys}}$
  (linear interpolation/extrapolation through 2 charm valence masses)

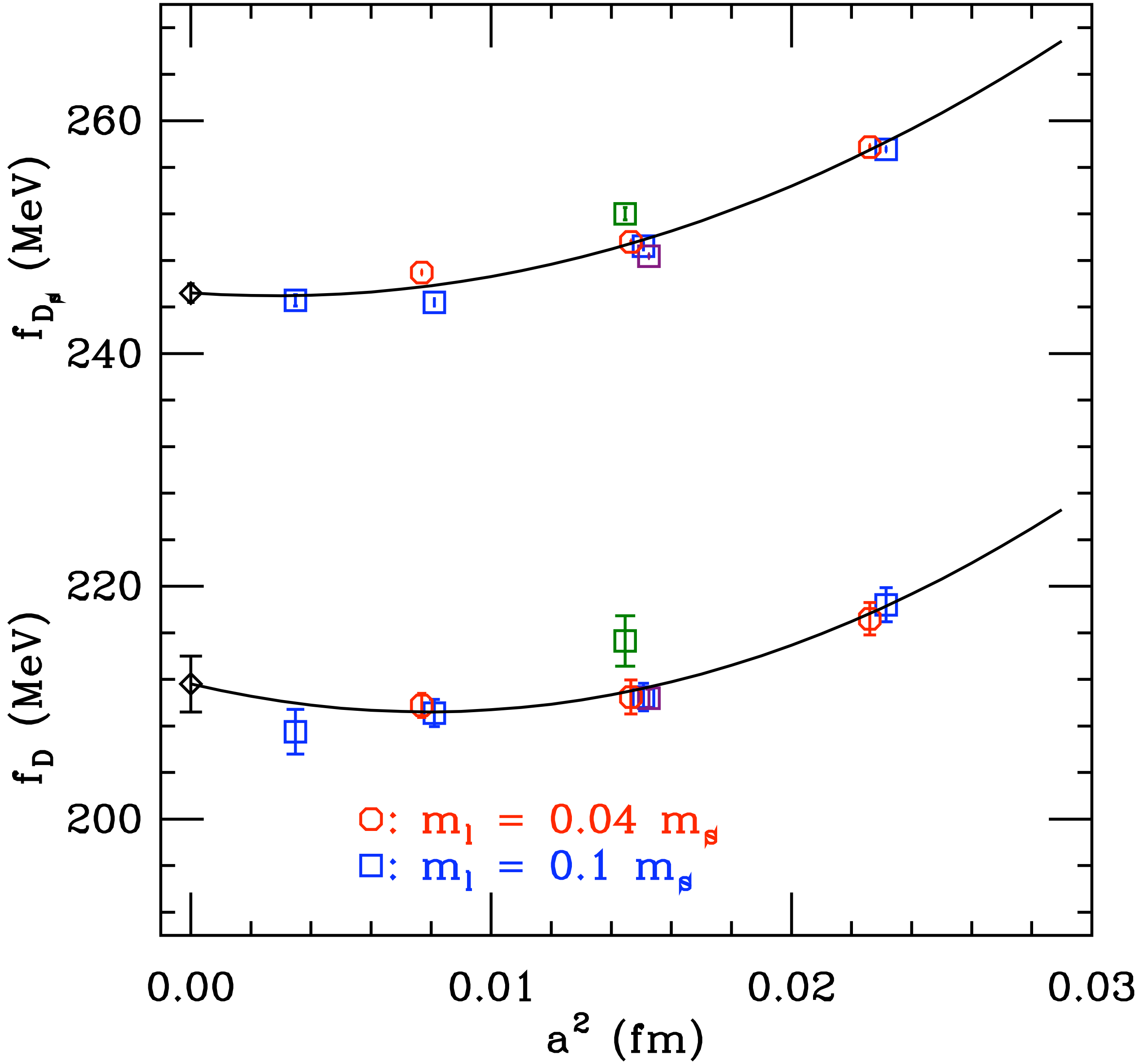
- $f \longrightarrow f_D$, $f \longrightarrow f_{D_s}$ at proper adjusted masses
  (linear interpolation in light, strange and charm masses)

HISQ f_D , f_{Ds}



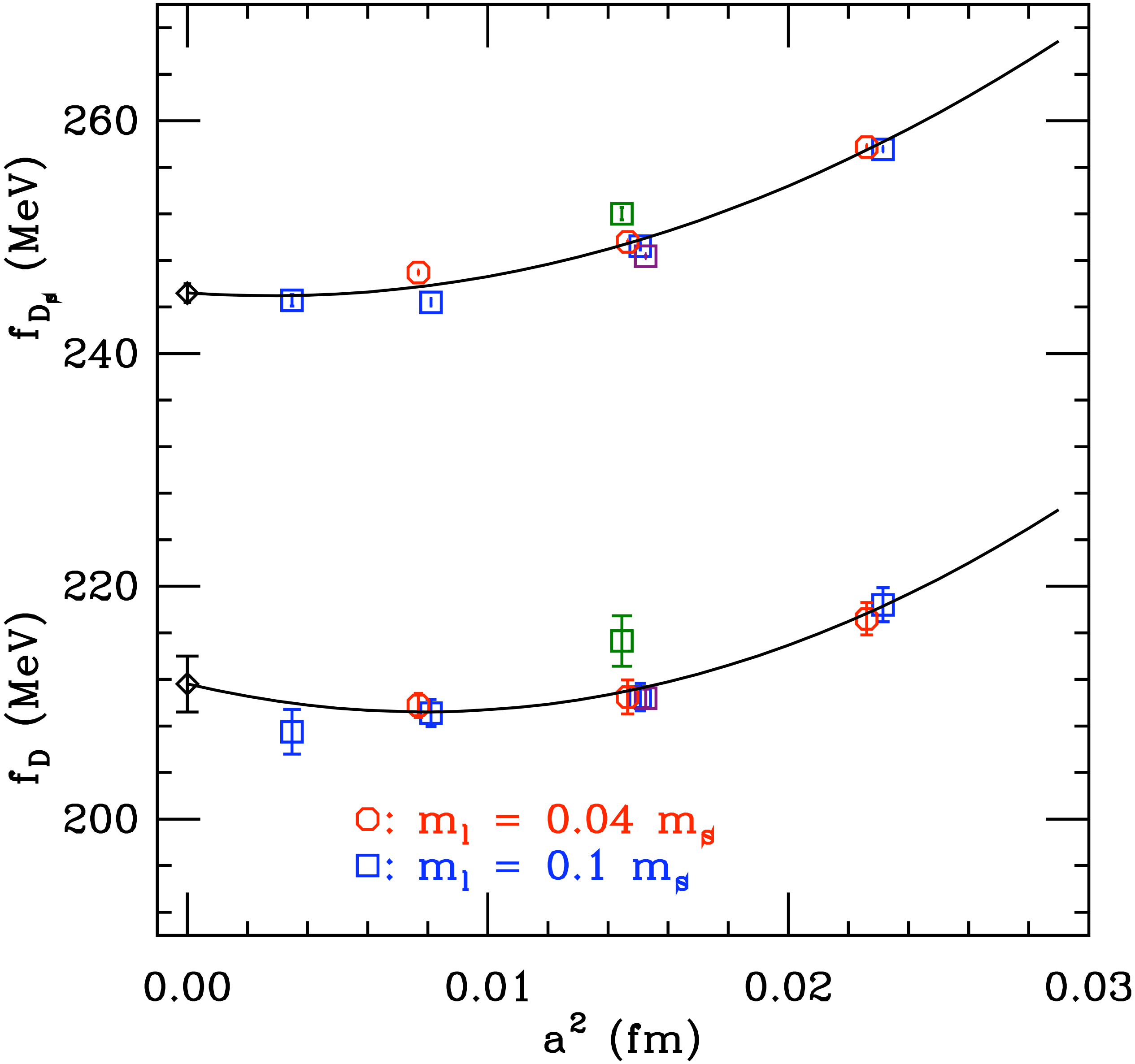
260
240
220
200
f_{D_s} (MeV)
f_D (MeV)
○: m_l = 0.04 m_s
□: m_l = 0.1 m_s
0.00
0.01
0.02
0.03
a^2 (fm)

HISQ f_D , f_{Ds}



quadratic continuum extrapolation and sea-mass chiral interpolation(!)

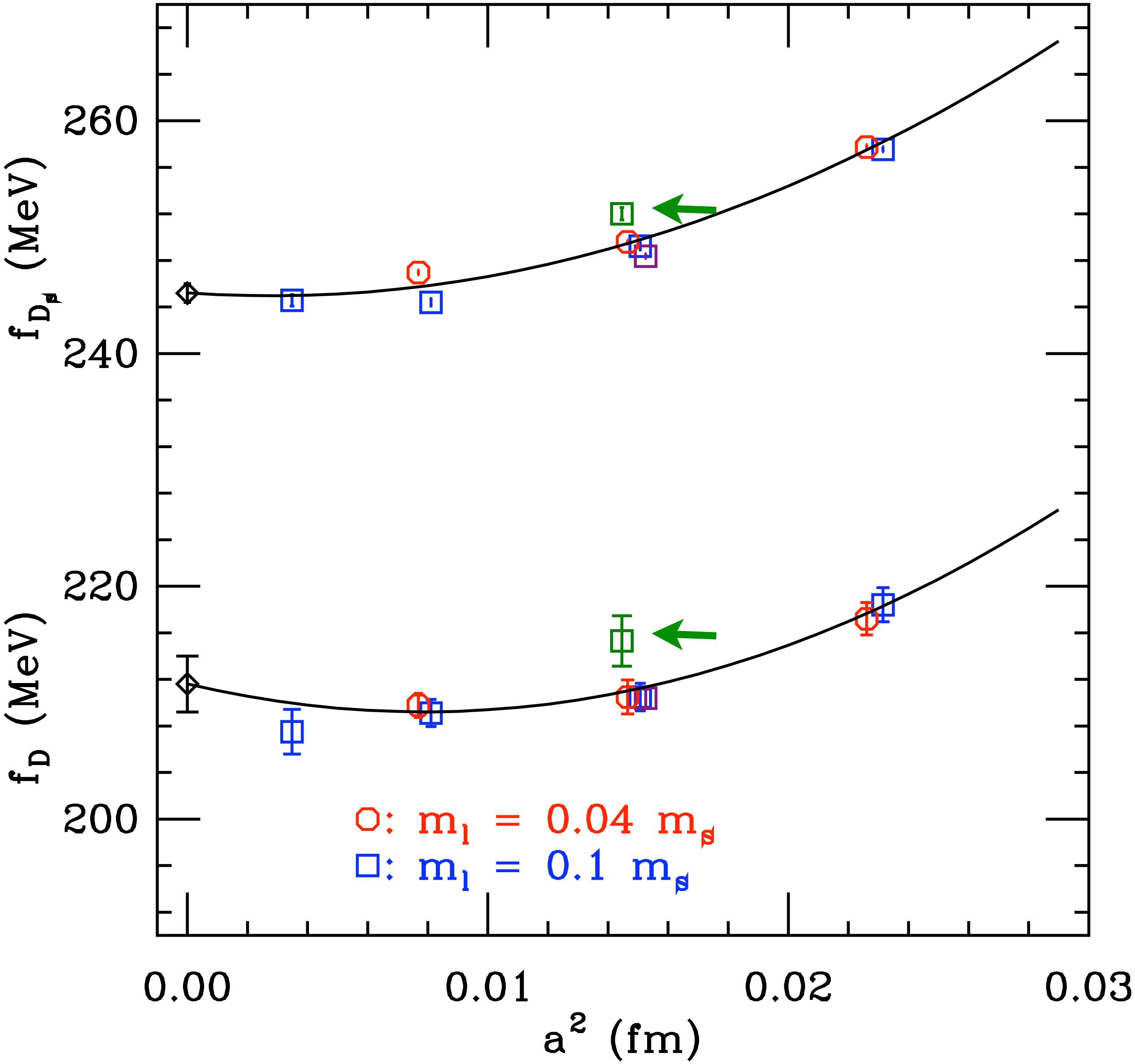
HISQ f_D , f_{Ds}



quadratic continuum extrapolation and sea-mass chiral interpolation(!)

finite volume effects:

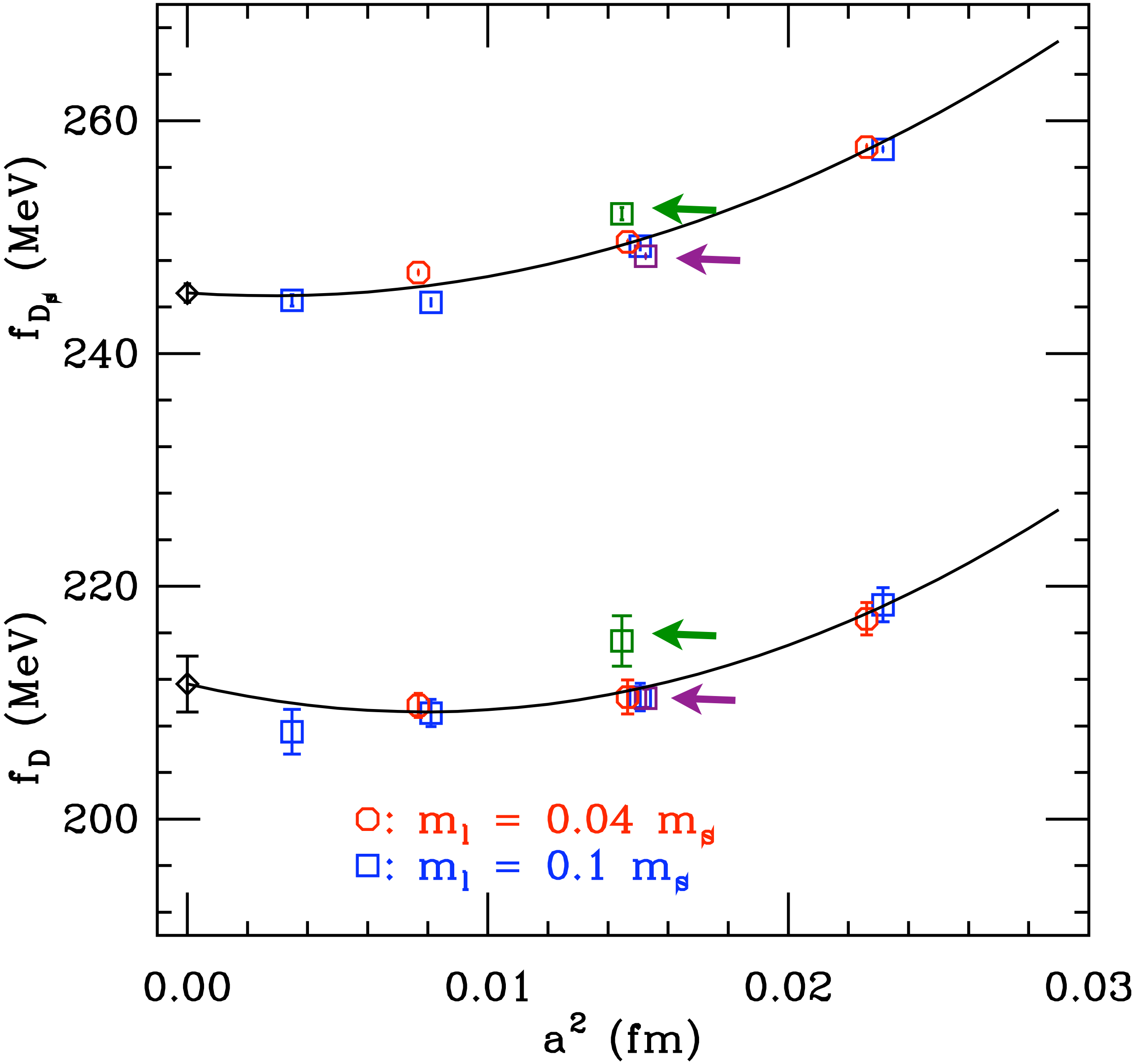
HISQ f_D , f_{Ds}



quadratic continuum extrapolation and sea-mass chiral interpolation(!)

finite volume effects:
smaller volume

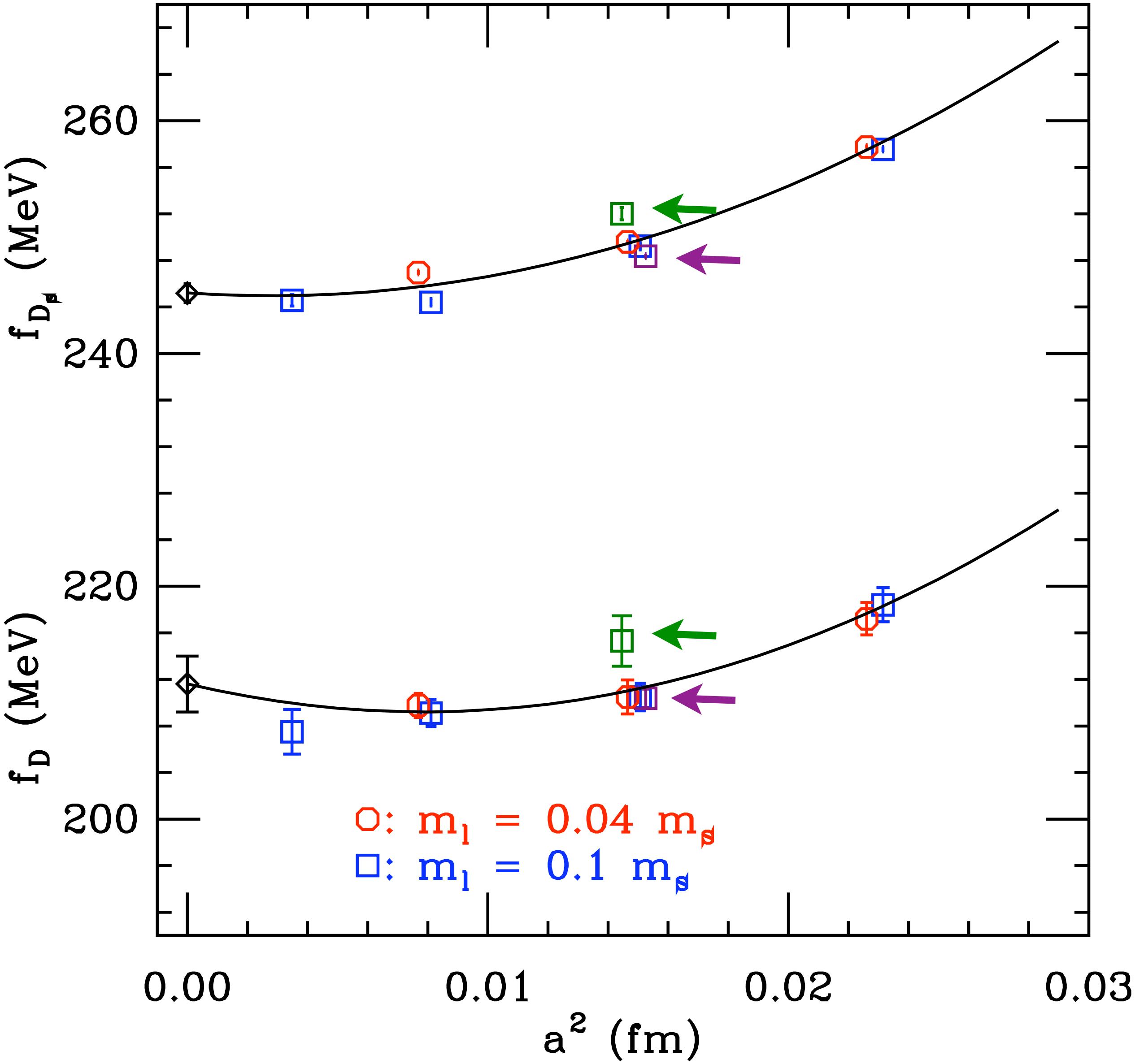
HISQ f_D , f_{Ds}



quadratic continuum extrapolation and sea-mass chiral interpolation(!)

finite volume effects:
smaller volume
larger volume

HISQ f_D , f_{Ds}

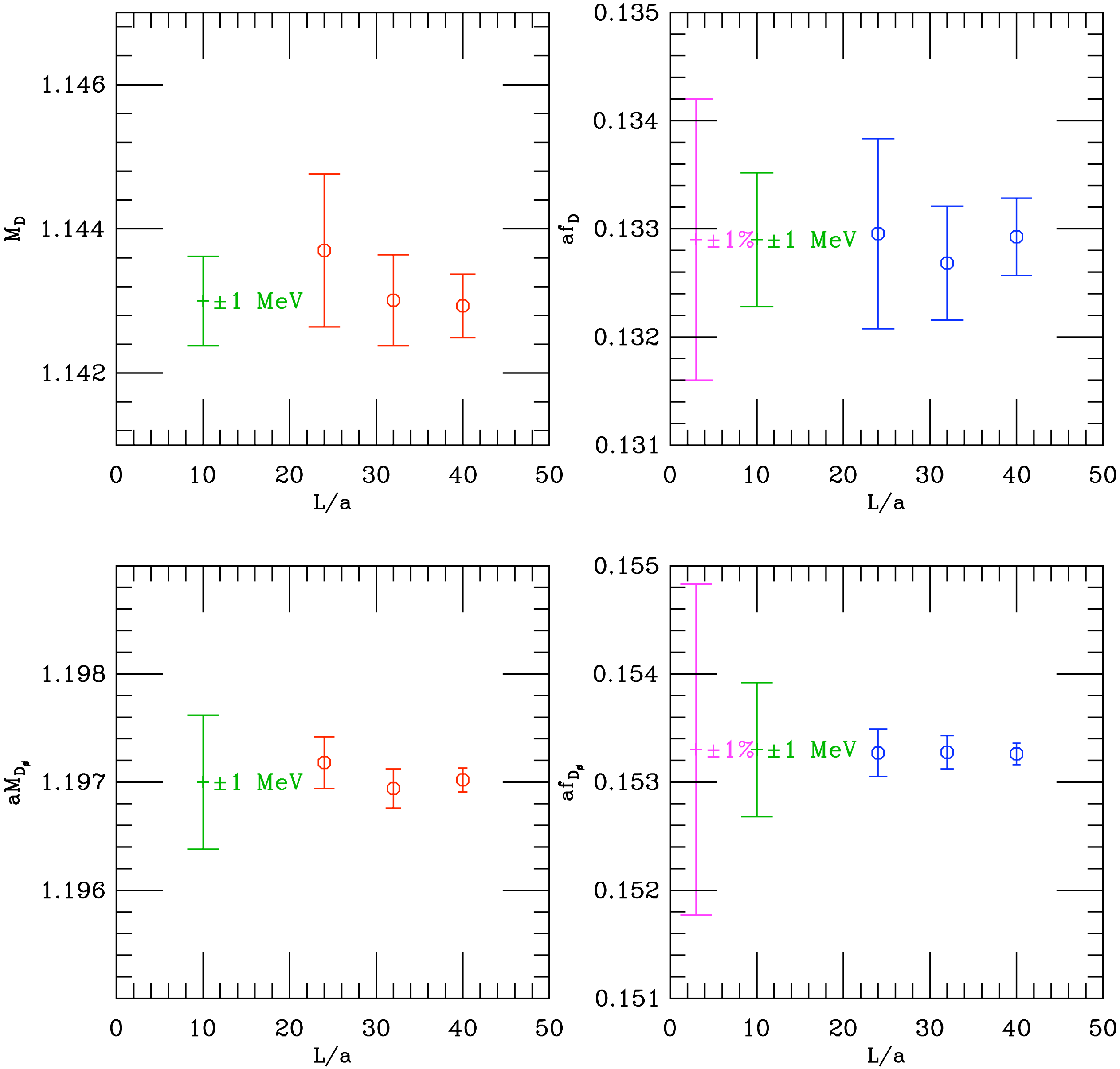


quadratic continuum extrapolation and sea-mass chiral interpolation(!)

finite volume effects:
smaller volume
larger volume

(primarily from f_π scale setting)

Finite size effects



- Not much evidence for finite size effects.
- Here, results are in lattice units.
    - Finite-volume effects can enter if scale is set in finite-volume-dependent way, e.g. f_π.

HISQ f_D , f_{Ds}

✦ Very preliminary results:

$$
\begin{aligned}
f_D &= 211.6 \pm 2.4 \pm ???\ \mathrm{MeV} \\
f_{D_s} &= 245.2 \pm 0.8 \pm ???\ \mathrm{MeV}
\end{aligned}
$$

- ??? are systematic errors, including:
    - continuum extrapolation/chiral interpolation
        - staggered ChPT has been worked out [CB and J. Komijani] and may help to control continuum extrapolation.
    - finite volume.
    - isospin: easy to determine valence isospin breaking, *e.g.*, f_{D+} vs. generic f_D .
    - EM effects: from Gläßle and Bali, arXiv:1111.3958 and Davies, et al., PRD 82 (2010) 114504, expect < 0.5%
        - ultimately plan to check with our EM code....

Outlook: Fermilab/MILC

	% Errors		
Quantity	"Old data" Fermilab (c,b) arXiv:1112.3051	"New data" Fermilab (c,b) (in progress)	HISQ (c) / Fermilab (b) (in progress)
f_{D_s}	4.2	2.2	1.0
f_D	5.2	2.8	1.5
f_{D_s}/f_D	2.1	1.1	0.5
f_{B_s}	3.9	2.6	~1.5?
f_B	4.5	2.8	~2.0?
f_{B_s}/f_B	2.1	1.2	~0.8?

Outlook: Fermilab/MILC

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HISQ valence & sea

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f_B	4.5	2.8	~2.0?
f_{B_s}/f_B	2.1	1.2	~0.8?

HISQ valence & sea

Fermilab B to D ratios + HISQ D (valence & sea)

Comment

- ✦ Best direction for us for B physics not obvious.
  - Use Fermilab or Oktay-Kronfeld (improved Fermilab) b quarks?
  - Push/extrapolate HISQ up to the b [HPQCD]?
  - Leverage HISQ data for D (or heavier D) by using Fermilab quarks for B/D ratios?
  - In any case, will eventually need non-perturbative or 2-loop matching for many quantities to match other systematic improvements.

$K \rightarrow \pi$ semileptonic decay

✦ Focus at $q^2=0$, where we can use the method HPQCD proposed for semileptonic D decay:

- Full matrix element of vector current V_μ is hard because conserved current is complicated and local current needs renormalization.
- Instead use $\partial^\mu V_\mu = (m_b - m_a)\, S$
  - S is local, and product $(m_b - m_a)S$ not renormalized.
- This is sufficient for $f_+(q^2=0) = f_0(q^2=0)$.

✦ Two-part program:

- HISQ valence on 2+1 Asqtad ensembles (close to completion).
- HISQ valence on 2+1+1 HISQ ensembles (early stage).
  - ultimately to include $D \rightarrow K$, and $q^2 \neq 0$

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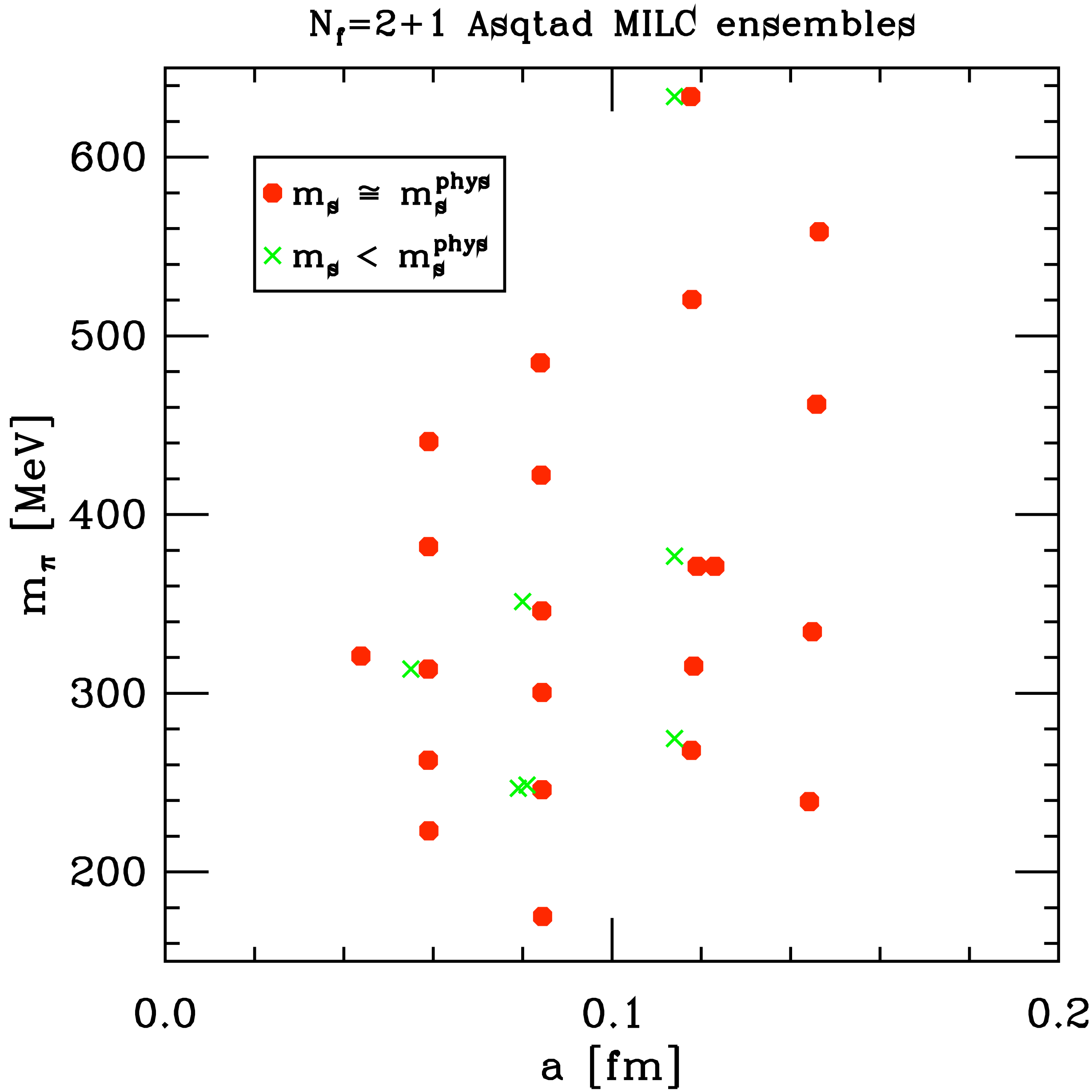
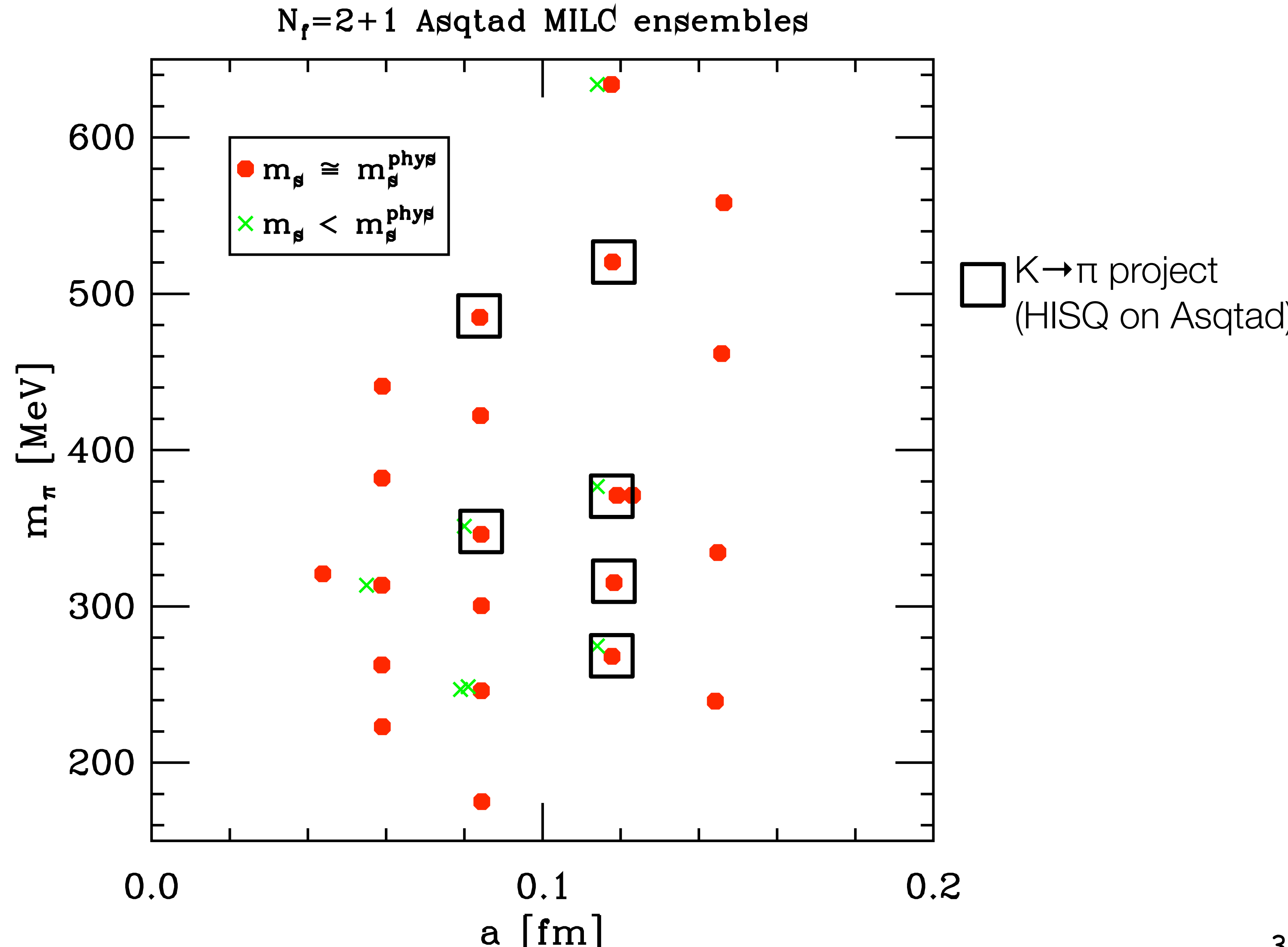
- Two-part program:
  - HISQ valence on 2+1 Asqtad ensembles (close to completion). [E. Gámiz]
  - HISQ valence on 2+1+1 HISQ ensembles (early stage).
    - ultimately to include $D \to K$, and $q^2 \neq 0$

Asqtad Ensembles



Asqtad Ensembles



K→π ; HISQ on Asqtad

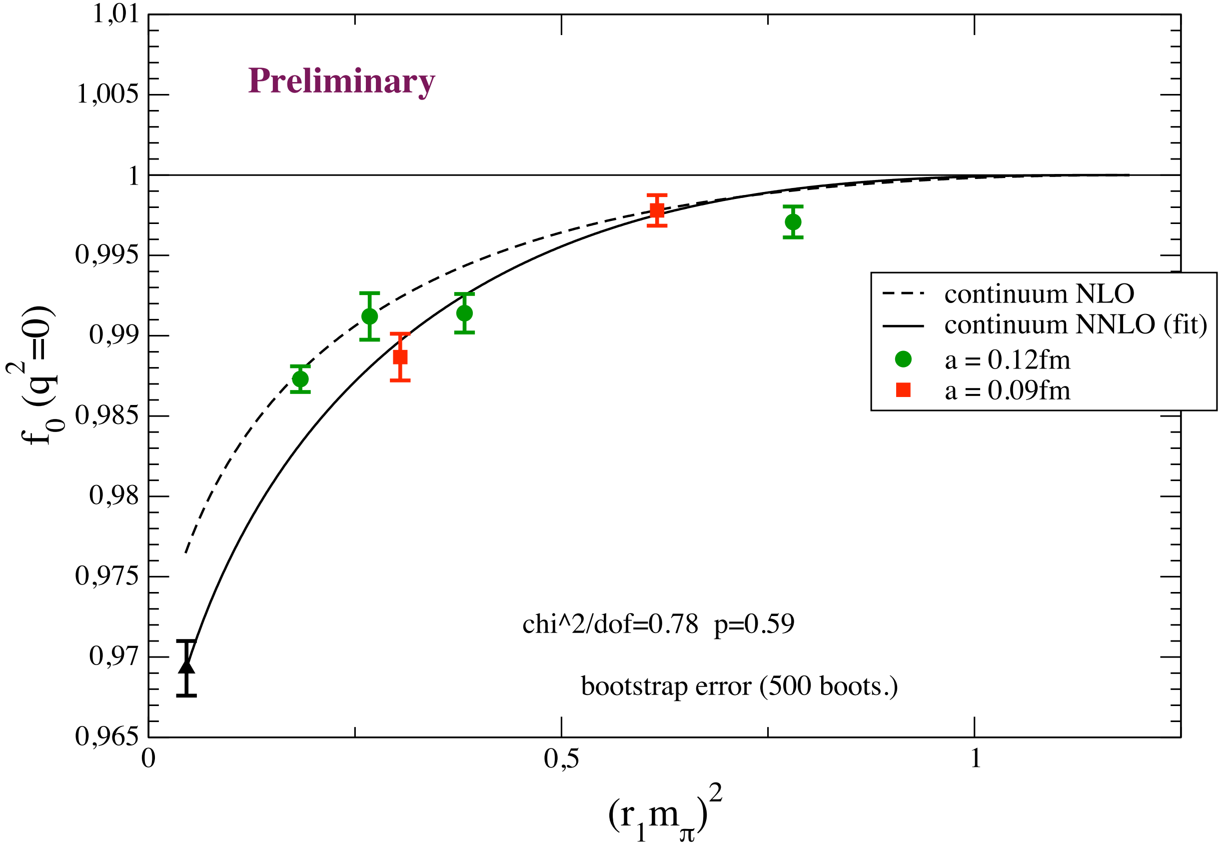
- Strange HISQ valence mass tuned to its physical value [from Davies, et al, PRD 81 (2010) 034506, using the "η_s"].
- Light HISQ valence mass tuned to Asqtad sea by:

$$\frac{m_l^{\rm val}(\rm Hisq)}{m_s^{\rm phys}(\rm Hisq)} = \frac{m_l^{\rm sea}(\rm Asqtad)}{m_s^{\rm phys}(\rm Asqtad)}$$

- So as close to "unitary" as possible for m_l in this mixed-action theory.
- Mixed-action SChPT at 1-loop has been calculated [E. Gámiz and CB], but still needs checking.

K→π ; HISQ on Asqtad

Sample Chiral Fit



- Statistical errors: ~0.2% -- 0.3%
- Different chiral fits tried so far agree within 1 stat. σ. E.g.:
  - 1-loop SChPT + 2-loop continuum ChPT.
  - 1-loop SChPT + higher order analytic.

- Need to understand the size of a^2 effects better; check SChPT.

$K \to \pi$; HISQ on Asqtad

- Expected error budget:
  - Statistical: 0.2--0.3%
  - Chiral extrapolation, fitting function: 0.1%
  - Discretization: 0.15%
  - Mistuning of m_s in the sea: 0.2%
- Total: 0.35%--0.5%, should be competitive with state of the art: RBC/UKQCD.

$K \to \pi$ semileptonic decay

- Focus at $q^2=0$, where we can use the method HPQCD proposed for semileptonic D decay:
  - Full matrix element of vector current V_μ is hard because conserved current is complicated and local current needs renormalization.
  - Instead use $\partial^\mu V_\mu = (m_b - m_a)\, S$
    - S is local, and product $(m_b - m_a)S$ not renormalized.
  - This is sufficient for $f_+(q^2=0) = f_0(q^2=0)$.
- Two-part program:
  - HISQ valence on 2+1 Asqtad ensembles (close to completion).
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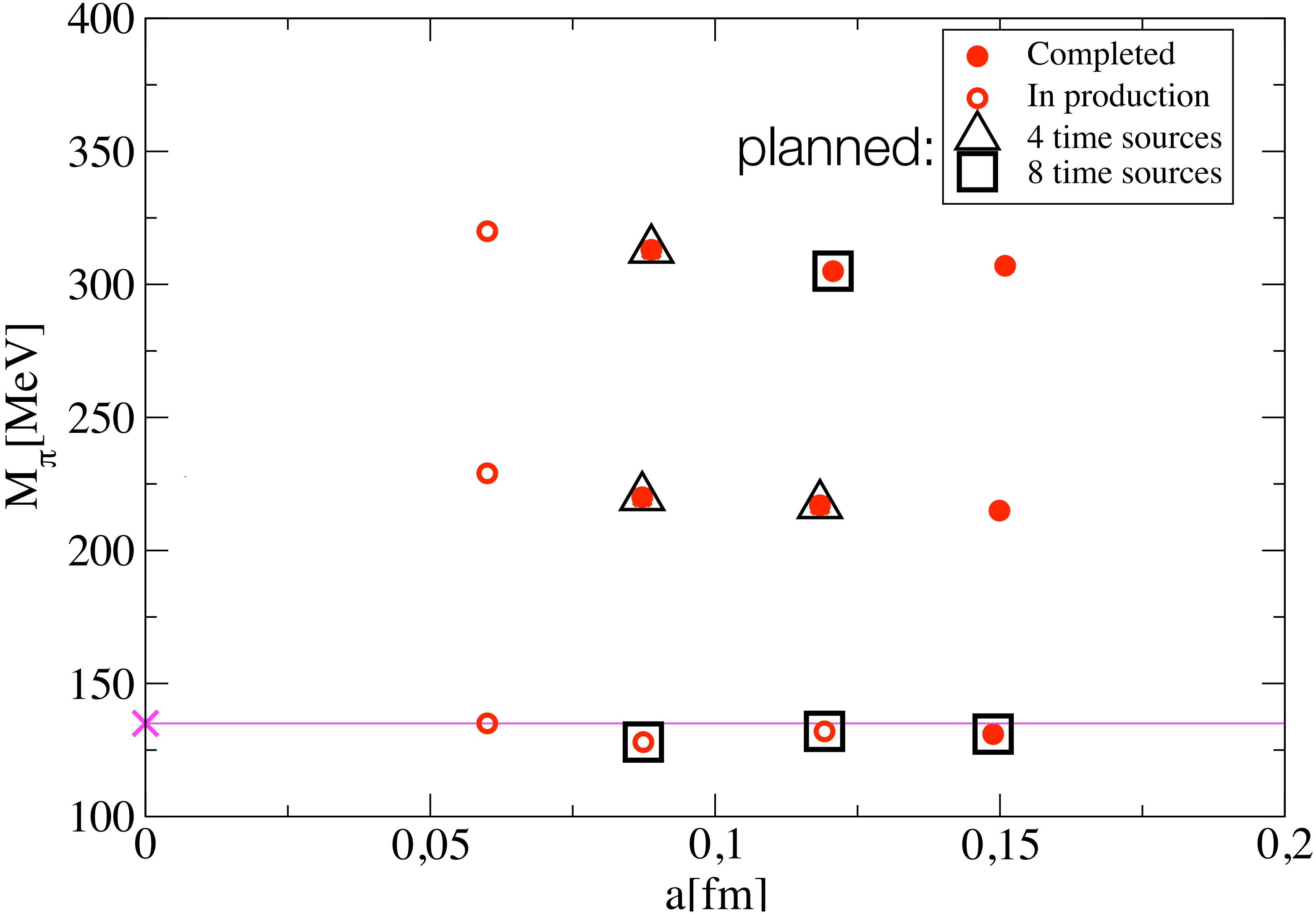
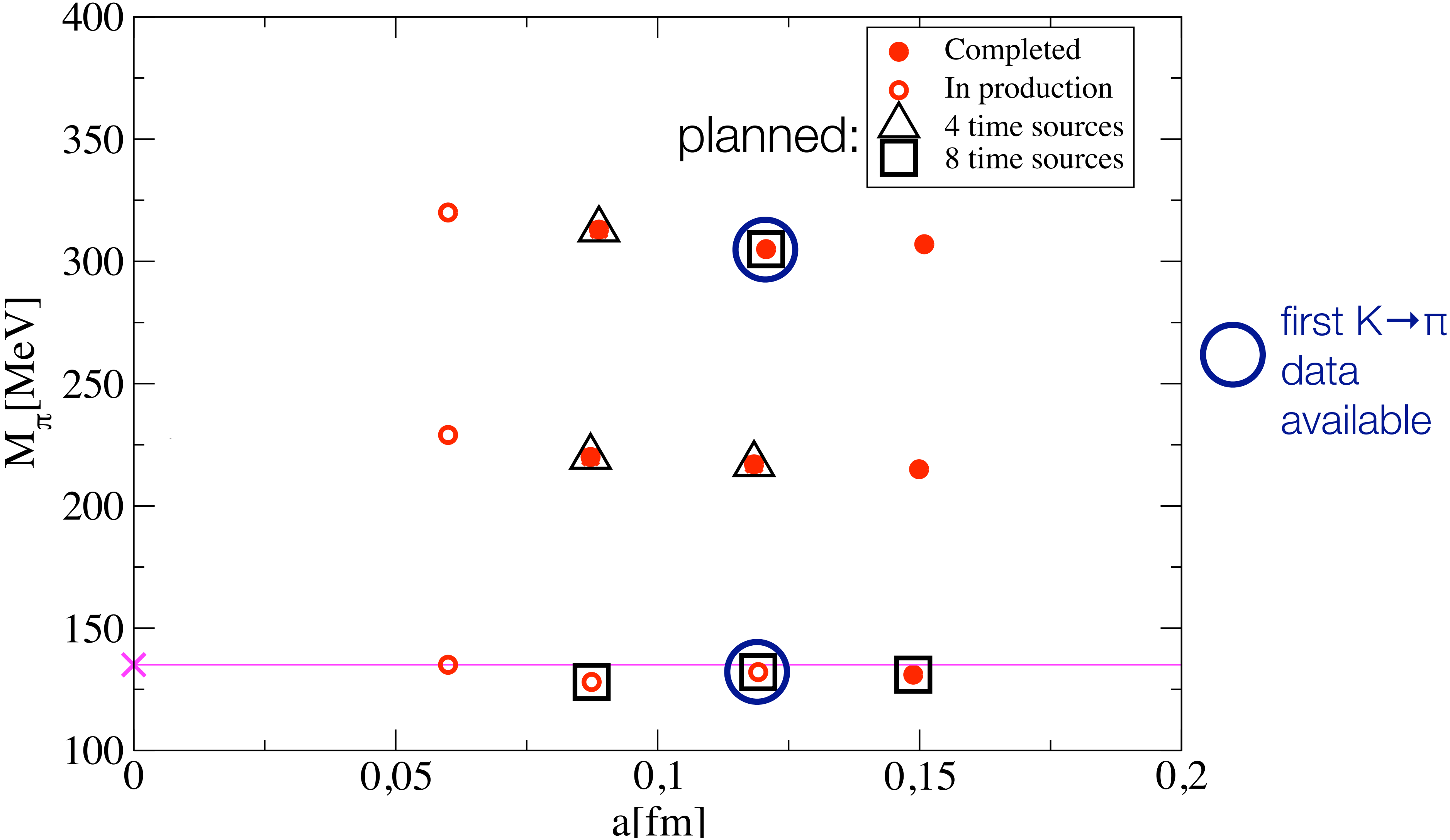
    - ultimately to include $D \to K$, and $q^2 \neq 0$

[E. Gámiz]

HISQ Ensembles

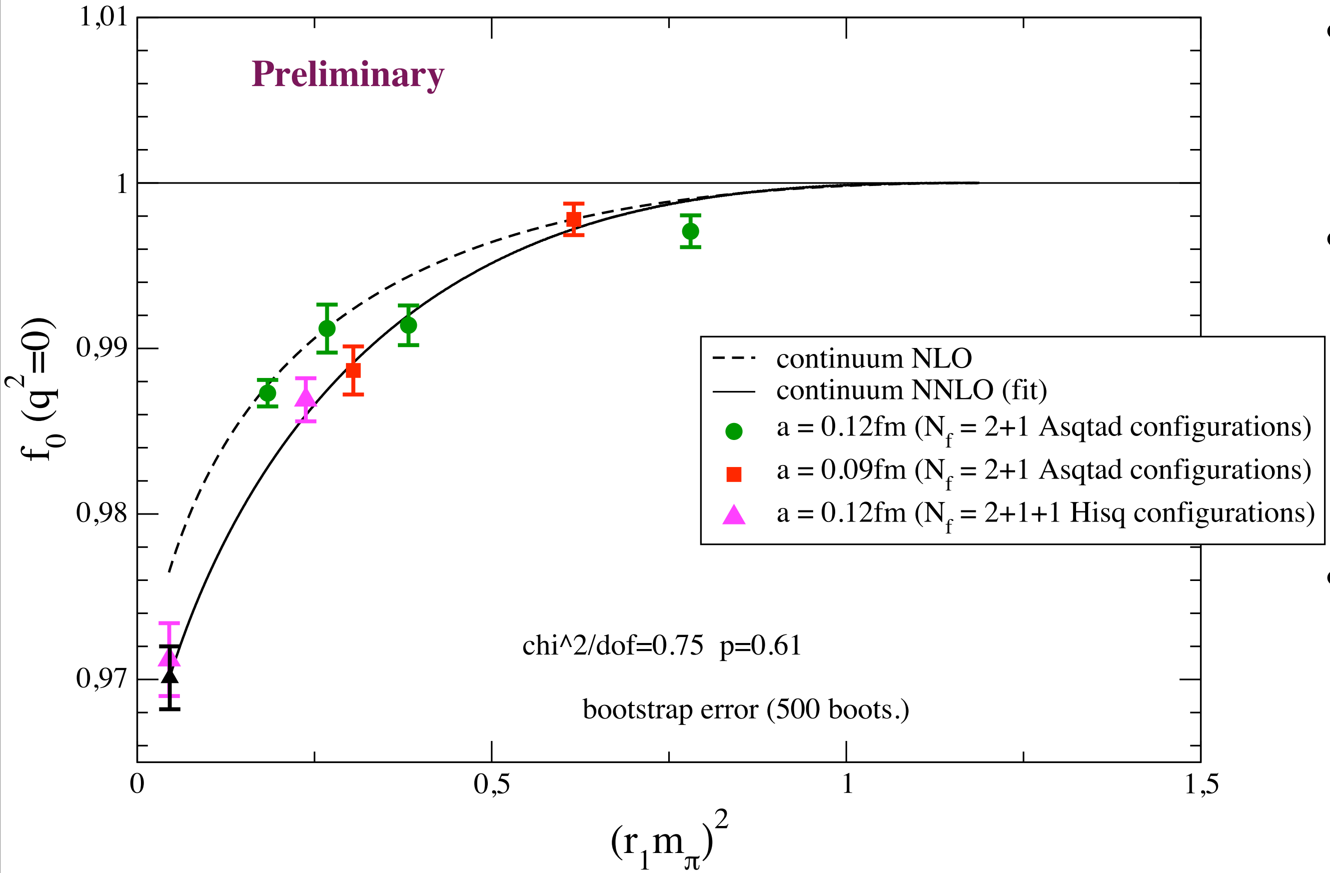


HISQ Ensembles



K→π : including HISQ on HISQ

Sample Chiral Fit



- Consistency with extrapolated HISQ on Asqtad results.
- Stat. errors larger on physical mass ensemble; momentum needed for q=0 is larger.
- Ensembles with heavier-than-physical u,d mass important for reducing final error.

- D→K being done in parallel, but fits not analyzed yet...

Some projects I didn't talk about:

Heavy-Quark Semileptonic Decays [Fermilab/MILC]

- $B \to D^* \ell \nu$ [arXiv:0808.2519, arXiv:1011.2166] (J. Laiho)
- $B \to D \ell \nu$ [arXiv:1111.0677] (S. Qiu)
- $B \to K \ell \ell$; $B \to K^* \gamma$ [arXiv:1111.0677] [R. Zhou; see his talk]
- $B \to \pi \ell \nu$ [arXiv:0811.3640] (R. Van de Water)
- $B_s \to \mu^+ \mu^-$ [using f for $(B_s \to D_s)/(B \to D)$; arXiv:1202.6346] (D. Du)
- $D \to \pi\ l \nu$, $D \to K l \nu$ [arXiv:0811.3640] (J. Bailey)

Quarkonia [Fermilab/MILC]

- [arXiv, 0912.2701, arXiv:1012.1837] (L. Levkova, C. DeTar, A. El-Khadra, E. Freeland,S. Gottlieb, A. Kronfeld,...)

Some projects I didn't talk about:

Electromagnetic Effects [MILC]

- ✦ Pseudoscalar mesons [arXiv:0812.4486, arXiv: 1011.3994, PoS(Lat10) 127] (S. Basak, A. Torok, S. Gottlieb, L. Levkova, E. Freeland, CB)
- ✦ Baryons (S. Gottlieb & students)

Strangeness content of the nucleon, *etc.* [MILC]

- ✦ Nucleon strangeness [arXiv:0905.2432, arXiv:1011.5271] (D. Toussaint, W. Freeman)
- ✦ Nucleon charm [arXiv:1204.3866] (D. Toussaint, W. Freeman)
- ✦ $\sigma_{\pi N}$ (D. Toussaint, W. Freeman)

Fermilab Lattice/MILC Collaboration

J. Bailey	Seule U.
A. Bazavov	U. of Arizona
C. Bernard	Washington U.
C. Bouchard	Ohio State
C. DeTar	U. of Utah
A.X. El-Khadra	U. of Illinois
R.T. Evans	U. of Illinois, North Carolina State U.
E.D. Freeland	U. of Illinois, Benedictine U.
W. Freeman	George Washington U.
E. Gamiz	Fermilab, U. de Granada
S. Gottlieb	Indiana U.
J. Komijani	Washington U.
U.M. Heller	APS
J.E. Hetrick	U. of the Pacific
J. Kim	U. of Arizona
A.S. Kronfeld	Fermilab
J. Laiho	U. of Glasgow
L. Levkova	U. of Utah
M. Lightman	Washington U.
P.B. Mackenzie	Fermilab
E. Neil	Fermilab
M.B. Oktay	U. of Utah
J. Simone	Fermilab
R. Sugar	U.C. Santa Barbara
D. Toussaint	U. of Arizona
R.S. Van de Water	BNL